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MICROWAVE POWER TRANSMISSION SYSTEM STUDIES

VOLUME I EXECUTIVE SUMMARY

RAYTHEON COMPANY
EQUIPMENT DIVISION
ADVANCED DEVELOPMENT LABORATORY
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Mr. Richard M. Schuh
NASA Lewis Research Center
Cleveland, Ohio 44135

16. Abstract
A study of microwave power generation, transmission, reception and control was conducted as a part of the NASA Office of Applications' joint Lewis Research Center/Jet Propulsion Laboratory five-year program to demonstrate the feasibility of power transmission from geosynchronous orbit. This volume (1 of 4) serves as an executive summary of results concerning design approaches, estimated costs (ROM), critical technology, associated ground and orbital test programs with emphasis on dc to rf conversion, transmitting antenna, phase control, mechanical systems, flight operations, ground power receiving-rectifying antenna with systems analysis and evaluation. Recommendations for early further in-depth studies complementing the technology program complete the volume.

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LIST OF NON-STANDARD TERMS

AFCRL	Air Force Cambridge Research Laboratory
ATC	Air Traffic Control
ATS	Applications Technology Satellite
CFA	Crossed Field Amplifier
CPU	Central Processor Unit
GaAs	Gallium Arsenide
HLLV	Heavy Lift Launch Vehicle
Met	Meteorological
MPTS	Microwave Power Transmission System
MW	Microwave
N. F.	noise factor
PPM	periodic permanent magnet
ROM	Rough Order of Magnitude
SCR	Silicon Controlled Rectifier
SEPS	Solar Electric Propulsion Stage
Sm-Co(SMCO)	Samarium Cobalt
SPS	Satellite Power System
SSPS	Satellite Solar Power Station
TDRS	Tracking and Data Relay Satellite
TEC	Total Electron Content

EXECUTIVE SUMMARY

This volume summarizes results obtained in the study concerning design approaches, estimated costs and technology requirements for systems that transmit power from space to earth, a concept leading to a potential source of comparatively pollution-free power. Basic elements of such systems are an extraterrestrial power source, e.g., a solar powered device or a nuclear reactor, and a transmission system to condition the power, beam it to earth and again condition it for distribution. The transmission system uses microwave technology which has the potential for high efficiency, large power handling capability and controllability. The transmitting antenna would be in geosynchronous orbit on a fixed line of sight to the ground antenna. The work was conducted in 1974-1975 by the Raytheon Company. Raytheon was supported by the Grumman Aerospace Corporation on mechanical systems and flight operations, and by Shared Applications, Inc. on klystrons for microwave conversion.

The transmitting antenna is a planar phased array about 1 km in diameter constructed of aluminum or composites and weighing about 6×10^6 kg. It consists of 18M x 18M slotted waveguide subarrays which are electronically controlled to direct the power beam at the ground receiving antenna with an rms error of only 10M. The subarrays use groups either of 5 kW amplitrons in series or 50 kW klystrons in parallel to convert input dc power to microwave power. The receiving antenna is an array about 10 km in diameter consisting of dipole elements each connected to a solid state diode which converts microwave power back to dc power.

An operating frequency of 2.45 GHz in the USA industrial band results in near optimum efficiency, avoids brownouts in rain and should have minimal problems in radio frequency interference and allocation. A 5 GW ground power output provides economy of scale while keeping the peak microwave power density in the center of the beam at earth about 20 mW/cm^2. Microwave system transmission efficiency is about 60% and cost is about 500 \$/kW including assembly and transport of the transmitting antenna to geosynchronous orbit at 200 \$/kg.

The orbital transportation and assembly cost should not exceed about 200 \$/kg if a satellite power system is to have energy costs comparable with projections for ground based fossil and nuclear plants. The recommended flight plan is transport to low earth orbit using a reusable heavy lift launch vehicle, assembly in low earth orbit and then transport to synchronous orbit using a solar electric propulsion stage. Emphasis is placed on orbital manufacture and assembly to achieve faborable launch vehicle packaging densities.

The critical technology items needing early development are the dc to microwave converters, materials, electronic phase control subsystems and the transmitting antenna waveguide and structure including their interfaces with the microwave converters. A

critical technology development and test program is presented. A ground test involving transmitting and receiving antennas is recommended to obtain data on beam controllability and radio frequency interference, which will provide design confidence for orbital tests. The planned orbital test program demonstrates operation of the open cathode dc to rf converter, satisfactory vacuum high voltage plasma interaction, orbital assembly techniques, and operations and maintenance development. The orbital test program for the microwave power transmission tech[illegible]ologies assumes availability of the Shuttle transportation system and a power source presumed to be a part of its own orbital test program.

1. INTRODUCTION

Microwaves can traverse the atmosphere with low attenuation, and advances in microwave power technology have been considerable since the first demonstration of appreciable power transfer by Brown (1963). The combination of a solar photovoltaic power source in geosynchronous orbit with microwave transmission to earth was first proposed by Glaser (1968). This Satellite Solar Power Station (SSPS) concept received increasing attention (J. Microwave Power, 1970; Brown, 1973) and led to a feasibility study conducted by a team consisting of Arthur D. Little, Inc., Grumman Aerospace Corp., Raytheon Co., and Textron Inc. under NASA sponsorship (Glaser, 1974). Results were sufficiently promising to warrant support of more detailed studies in the technologies involved.

The study concentrated on the microwave power transmission system (MPTS) for transmitting energy from space to earth, and as such the results are independent of the power source selected. For examples, a solar thermal converter or a nuclear reactor in orbit could be considered in place of a solar photovolataic source. Nevertheless, the solar photovoltaic source remains the best known and studied of alternatives, and so was used for purposes of illustration where required. The study involved preliminary analysis, conceptual design, technical and economic evaluation, and planning for a technology development, a ground demonstration and an orbital test program.

The concept of space to earth microwave power transmission is illustrated in Figure 1. A transmitting antenna in geosynchronous orbit beams microwave power to a ground antenna where it is rectified to dc power. Functional blocks of such a power transmission system are shown in Figure 2. Efficiency is a prime consideration in any transmission system, and it is evident that elements must average over 90% if overall efficiency is to be a modest 60%. These efficiency considerations dictate that the antennas be extremely large scale, e.g., the transmitting antenna is on the order of 1 km in diameter and the receiving antenna is on the order of 10 km, because of the long transmission distance of 37000 km. This scale implies that large units of power, on the order of 5 GW-10 GW, must be transferred and that the power source in turn must be very large scale.

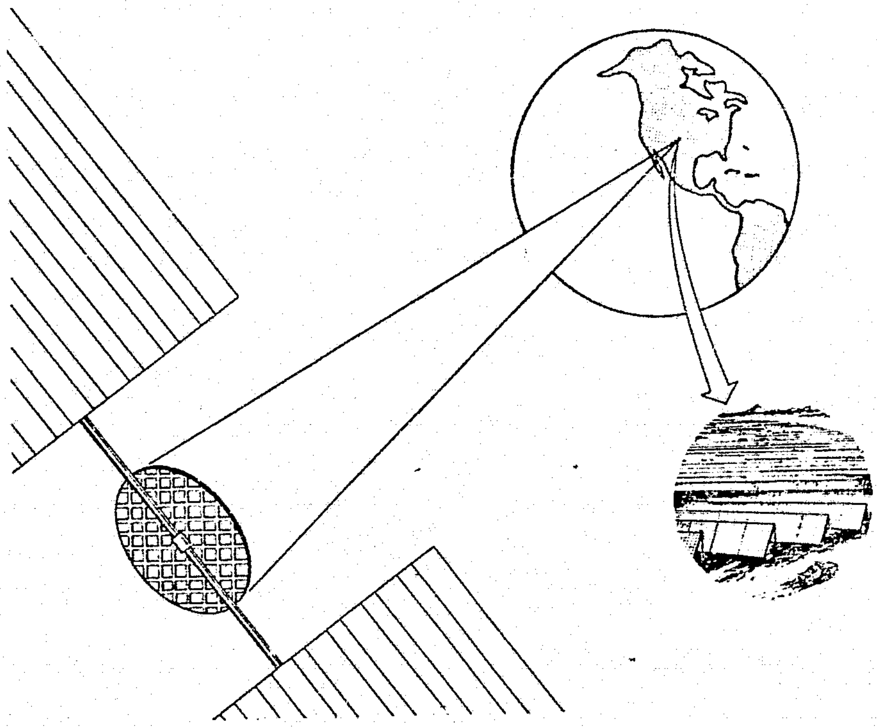

Figure 1 MPTS Concept

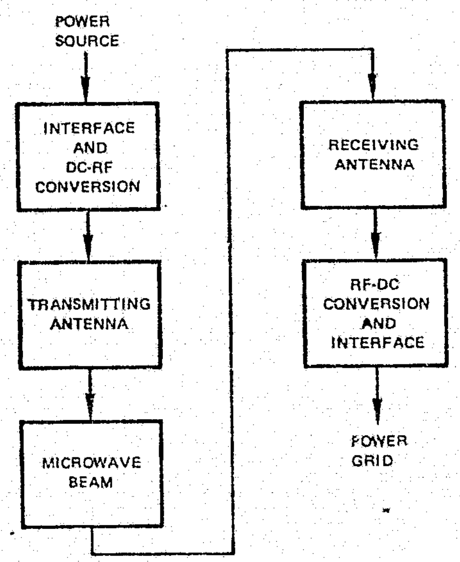

Figure 2 MPTS Functional Diagram

High efficiency requirements also dictate the band of microwave frequencies that can be considered. The effect of molecular absorption shown in Figure 3 limits frequencies to below 10 GHz to 16 GHz. The upper limit reduces further if brownouts in light rain (5 MM/HR) are to be excluded, and the avoidance of brownouts in heavy rain and severe thunderstorms, for which attenuations are shown in Figure 4, would place an upper limit not far above 3 GHz. The severe rain conditions are experienced even in the desert locations that are prime candidates for the ground receiving antenna location.

Having introduced scale and frequency considerations, we proceed to examine the technical and cost aspects of the major systems building blocks, then discuss the transportation and assembly of the orbital elements, present a selection of recommended system parameters based on overall economic and technical considerations, and finally summarize the areas of critical technology requiring priority attention in the future. A 30 year useful life is taken as a design goal for candidate configurations.

2. DC TO RF CONVERSION

The study examined two generic types of devices for converting dc power to rf power at microwave frequencies: the amplitron, or crossed field amplifier (CFA), and the klystron, a linear beam device. In current usage the amplitron is characterized by high efficiency and low gain; the klystron is known for moderately high efficiency, high gain and low noise.

A cross section view of an amplitron designed for the MPTS application is shown in Figure 5. Special features of the design include open construction for low weight and reliability, and a platinum metal cathode operating on the principle of secondary emission to achieve an essentially infinite cathode life. Tube dc voltage input is 20 kV. Samarium Cobalt magnets provide a very low specific weight, and pyrolytic graphite with low density and high emmissivity radiates waste heat to space. The only element with a potential wearout mechanism is the movable magnet shunt designed for regulating the output as input voltage fluctuates. A regulating concept eliminating moving parts by using an impulse magnetic control is proposed as an alternative approach.

Specific weight, specific cost and efficiency trends with frequency as a variable are shown in Figure 6. These favor a selection near 2.45 GHz which is in the center of the industrial microwave band of 2.40 GHz - 2.50 GHz. An output power level selection at 2.45 GHz should be near 5 kW as indicated in the weight and cost trends of Figure 7. The dominance of the thermal radiator in overall weight is indicated in the breakdown of Figure 8 for a 5 kW, 2.45 GHz amplitron. The pyrolytic graphite radiator is sized by an 85% tube efficiency and by the maximum temperature (350°C) allowed for the Samarium Cobalt magnet. Power budget for the MPTS amplitron is given in Figure 9. Improvement to 90% efficiency is believed a reasonable development goal since amplitrons already have reached 85% [Brown, 1974].

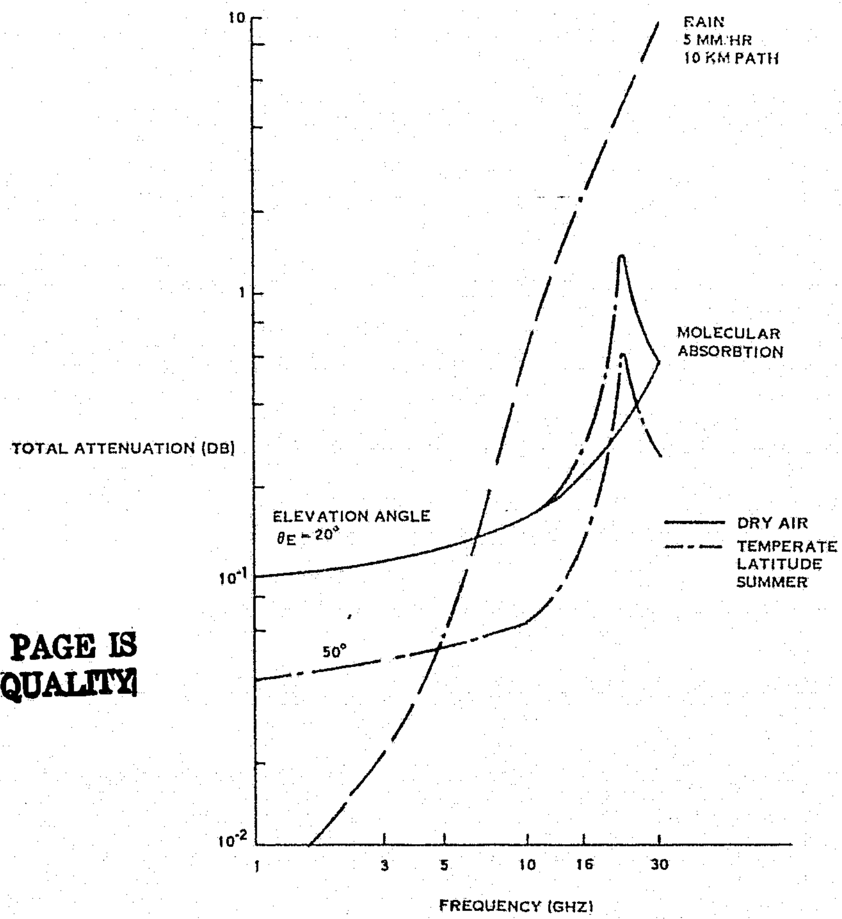

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Figure 3
Comparison of Gaseous Absorption and Rain Attenuation

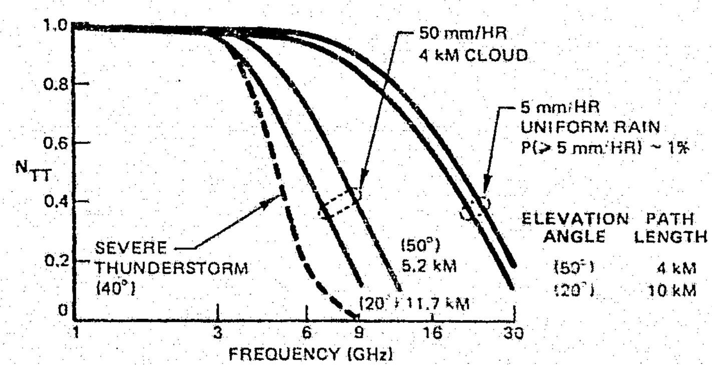

Figure 4
Transmission Efficiency - Molecular Absorption and Rain

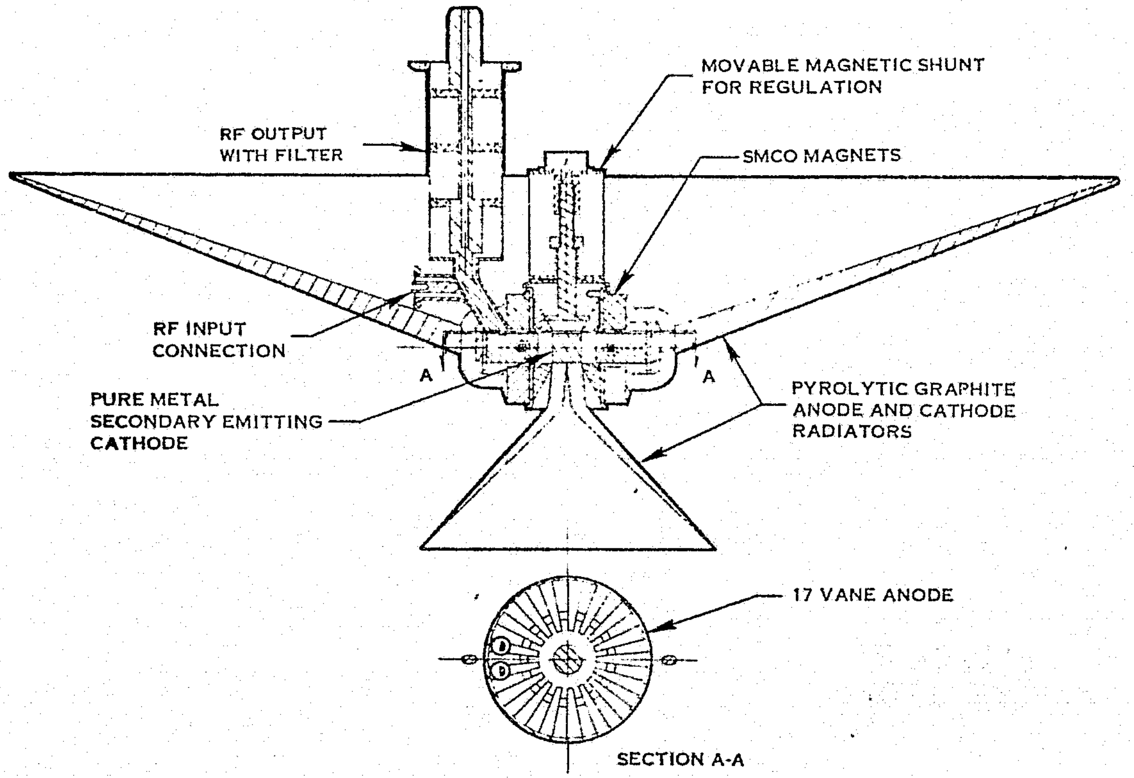

Figure 5 Amplitron Assembly

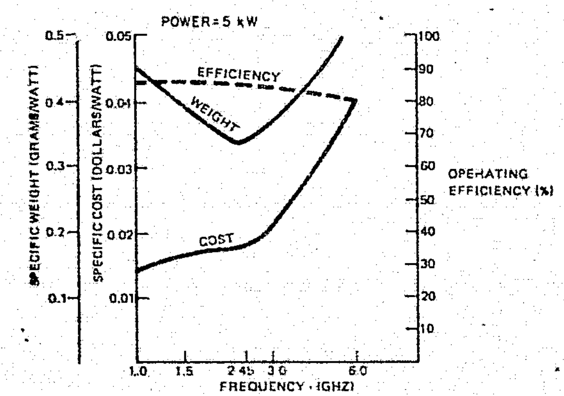

Figure 6 Amplitron Weight/Cost/Efficiency Vs. Frequency

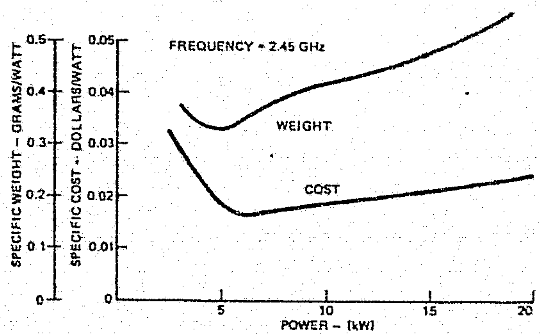

Figure 7 Amplitron Weight and Cost Vs. Power

ANODE	108 GRAMS
ANODE RADIATOR	1000
CATHODE	9
CATHODE RADIATOR	71
MAGNET	260
POLES	100
INPUT AND OUTPUT	40
MOTOR AND DRIVE	30
	1618 GRAMS – 3.56 LB
SPECIFIC WEIGHT	0.33 g/w
SPECIFIC COST	0.018 $/w

Figure 8 MPTS 5 kW Amplitron Parameters

RF POWER ADDED	5000 WATTS
ANODE ELECTRON BOMBARDMENT	371
ANODE CIRCUIT LOSSES	177
CATHODE DISSIPATION	199
DC INPUT POWER	5747 WATTS
GROSS EFFICIENCY	87%
OUTPUT FILTER DISSIPATION	125 WATTS
NET EFFICIENCY	85%

Figure 9 MPTS 5 kW Amplitron Power Budget

Preliminary studies of the klystron indicated the 1.5 GHz to 3 GHz region would yield relatively low specific weight and cost designs as was the case for the amplitron. They also showed a possibility of purely passive cooling at power levels below 10 kW, but further study indicated all klystrons would require at least a heat pipe cooling scheme. Attention then shifted from low power, permanent magnet-focused tubes to higher power tubes of the solenoid-focused type where focusing power becomes less significant in the power budget. This trend is shown in Figure 10.

A klystron design at 2.45 GHz representative of the higher power versions is shown in cross section for a 48 kW tube in Figure 11. Like the amplitron the tube would be open construction. Most power loss occurs at the collector where it is radiated at high temperature. However, removing heat from the body is a difficult challenge, solved in this example by using heat pipes which remain to be detailed in future studies. The tube incorporates a hot cathode which must be designed to achieve a life commensurate with a 30 year system life. Cold cathodes have not been demonstrated in klystrons as they have in amplitrons, although they might be realized by further development.

The power budget and tube parameter summary in Figures 12 and 13 indicate that relative to the amplitron, efficiency is about four percent lower, specific weight is three hundred percent higher and specific cost is slightly higher. However, the klystron may have two potential advantages over the amplitron: (1) fewer, higher power tubes may simplify the orbital assembly task and (2) low noise and narrow bandwidth reduce radio frequency interference.

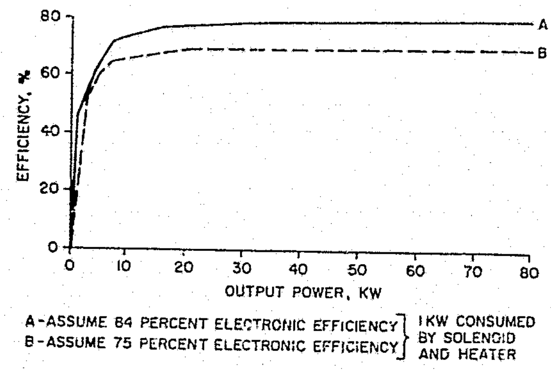

Figure 10
Efficiency Vs Output Power for Solenoid-Focused Klystron

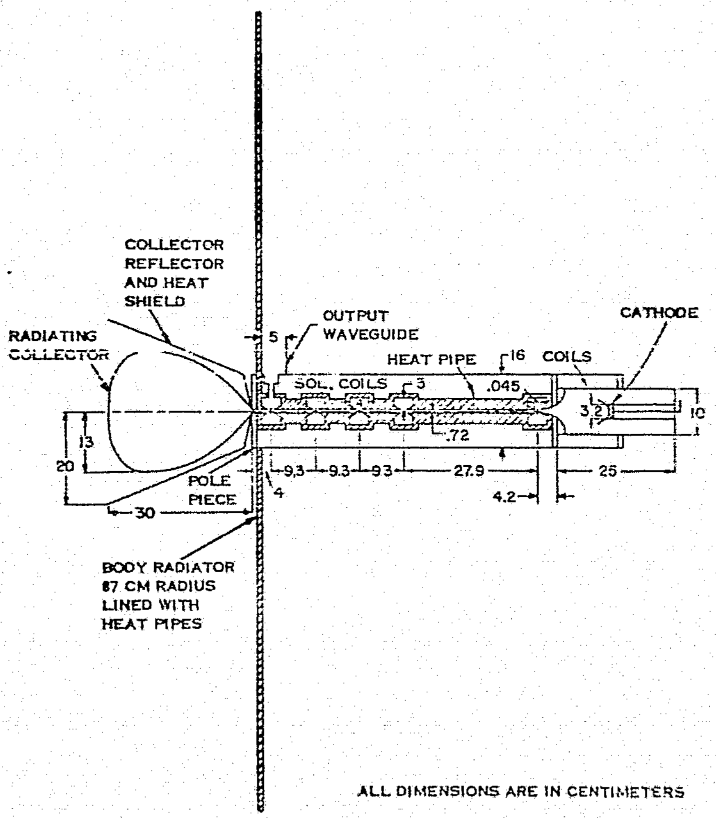

Figure 11
Outline of 48 kW Klystron with Solenoid Focusing

ELECTRICAL	
VOLTAGE	38.9 KV
CIRCUIT	1.54 A
GAIN	31 dB
MICROPERVEANCE	0.2
WEIGHTS	
MAGNET PLUS POLE PIECES	16300 GRAMS
TUBE	32374
TOTAL	48674 GRAMS
SPECIFIC WEIGHT	1.01 g/w
COST	
SPECIFIC COST	0.039 $/w

Figure 12 MPTS 48 kW Klystron Parameters

OUTPUT POWER	48362 WATTS
OUTPUT CAVITY LOSSES	
SKIN LOSSES	2038
INTERCEPTION	384
OTHER INTERCEPTION	461
HEATER POWER	60
SOLENOID	1000
COLLECTOR DISSIPATION	8755
TOTAL BEAM POWER	60000 WATTS
OTHER POWER	1060
TOTAL INPUT	61060 WATTS
NET EFFICIENCY	79.2%

Figure 13 MPTS 48 kW Klystron Power Budget

3. TRANSMITTING ANTENNA AND PHASE FRONT CONTROL

Goubau and Schwering [1961] showed theoretically that microwave power can be transferred at high efficiency when the transmitting antenna is illuminated with an amplitude distribution that is near Gaussian, as illustrated for the MPTS in Figure 14, and when the phase front of the beam is focused on the receiving antenna. For the extreme transmission distance from geosynchronous orbit, the curvature of the phase front is very slight, but nevertheless the front must be controlled with high precision to maintain high efficiency.

Figure 15 shows the effect of the transmitting antenna amplitude taper (from antenna center to its edge) on receiving antenna dimension for several high beam interception efficiencies. We can expect that attractive combinations will be found in the 5 dB to 10 dB range to limit the size of the receiving antenna while achieving high efficiencies. It is interesting to note that other microwave applications generally use a uniform illumination, or 0 dB taper, which achieves maximum intensity in the center of the beam but also places a higher proportion of power in sidelobes. This trend is illustrated in Figure 16.

The recommended approach to control of the phase front to the required precision requires that the antenna be sectored into numerous subarrays. A typical quadrant for an antenna on the order of 1 km is shown in Figure 17, which also gives an example of how the array could be organized to provide the necessary center to edge amplitude taper. Figure 18 illustrates the factors entering into the choice of subarray size. Large subarrays individually have narrow, high gain radiation patterns that will result in large power loss if the overall array is mechanically offset to a substantial degree from pointing to the ground, due for example to attitude control limit cycling. This power loss cannot be offset electronically, so smaller more numerous subarrays are selected, as shown. (Total radiated power remains the same.) Phase control electronics must be present in each subarray (definition of a subarray) so that

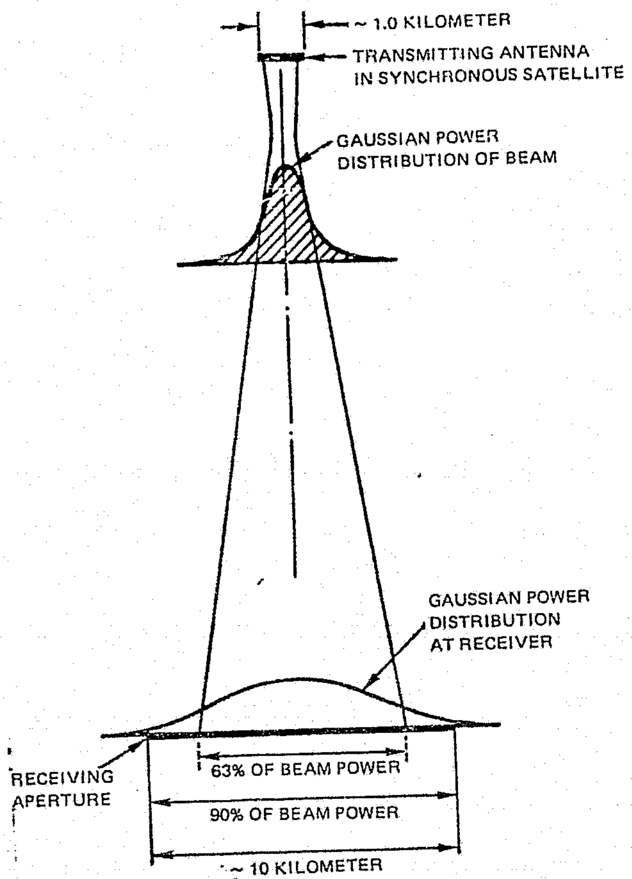

Figure 14 Microwave Power Beam - Idealized

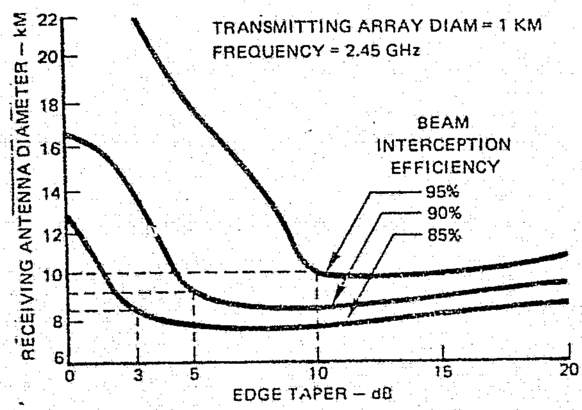

Figure 15
Receiving Antenna Sizes for Truncated Gaussian Beam Tapers

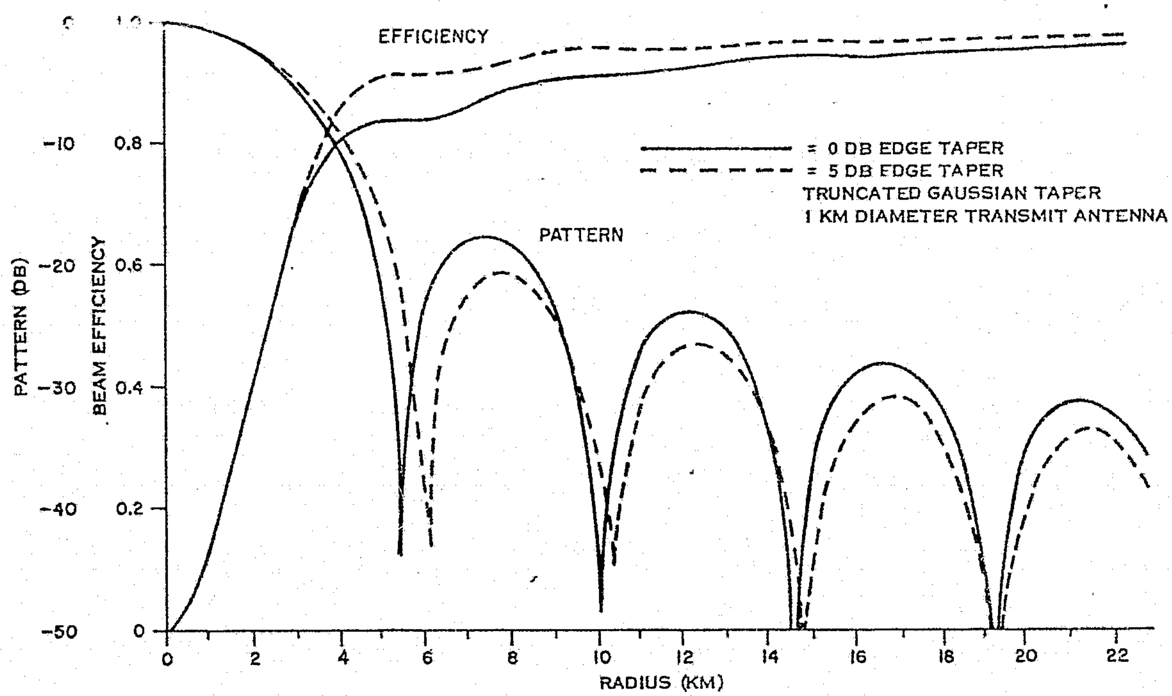

Figure 16 Taper Effect on Pattern and Efficiency

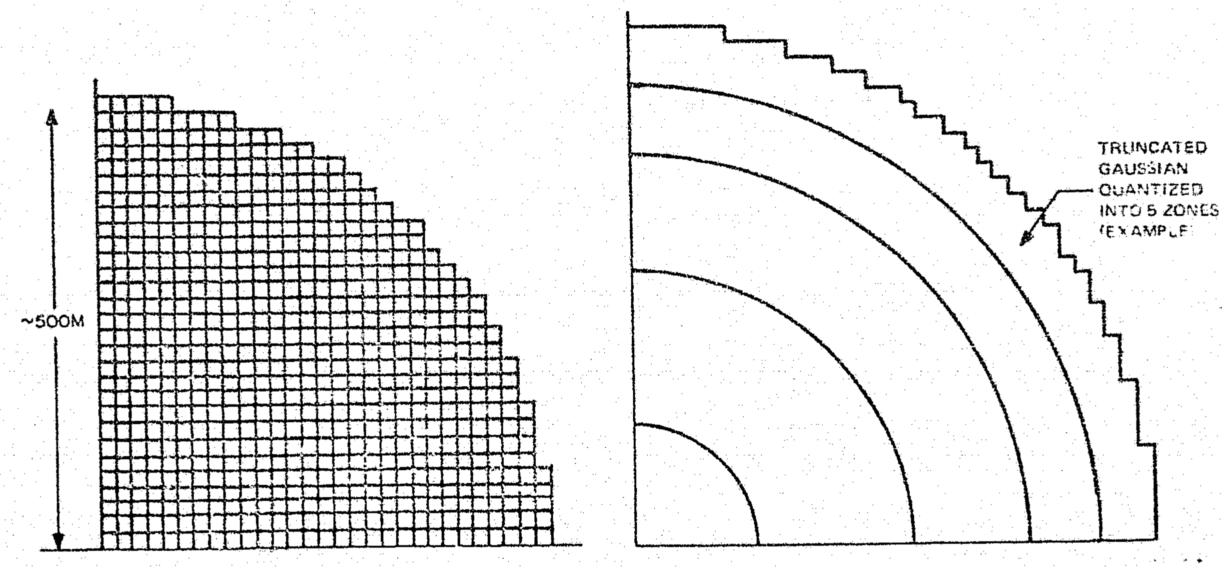

Figure 17 Array-Subarray Organization

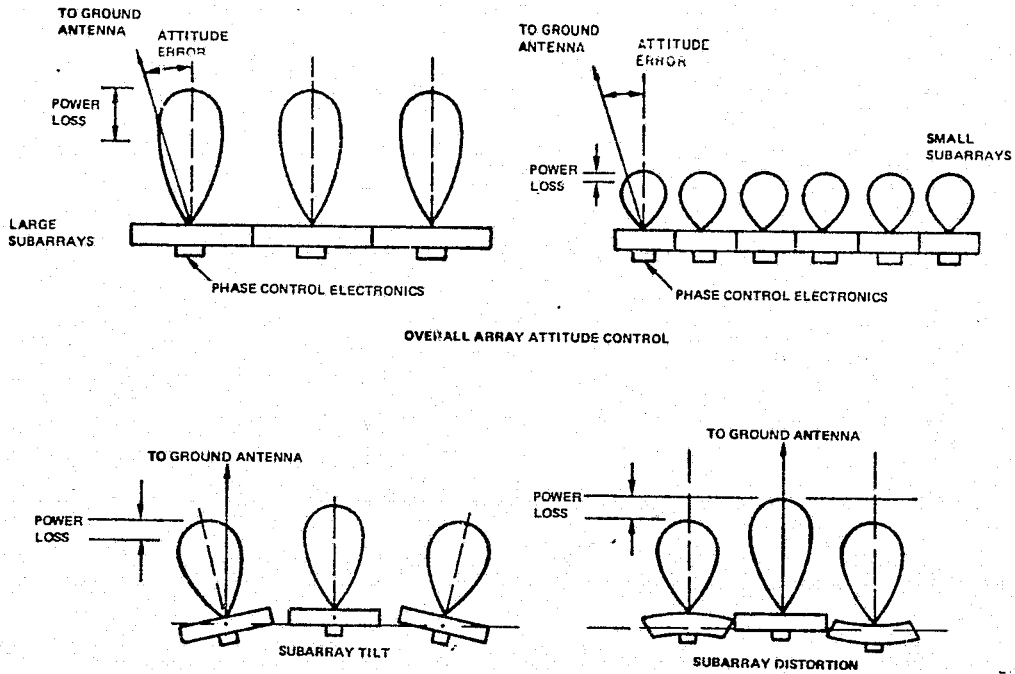

Figure 18 Subarray Size Considerations

there will be a tradeoff of power loss vs controls cost. Figure 18 also shows other factors producing power loss: subarray tilt relative to the overall array nominal position, and subarray distortion, both of which will be strongly influenced by thermal effects.

Efficiency and safety needs dictate that a closed loop form of control be implemented for phase front or beam formation. Two approaches, adaptive and command, have been formulated and are illustrated in Figure 19. The command system uses a matrix of sensors at the ground antenna to determine the received power beam center and shape. A processor then develops commands which are routed to the subarrays over the telecommunications link. This approach has limited resolution, but nevertheless it is anticipated that antenna thermal distortions, a major source of error, can be accurately modeled and suitable command algorithms developed. In any event it will serve as a system monitor and as a safety override function.

A potentially more accurate scheme calls for a reference beam to be launched from the center of the ground antenna. This is sensed at each subarray and at a reference subarray in the antenna center. The latter transmits the reference to the subarray over a calibrated coaxial cable at which point it is compared with the incoming beam. A difference in phase between these signals is interpreted as a displacement of the subarrays from the nominal reference plane, due for example to thermal distortion of the structure, and a correction is applied to the phase of the transmitted beam at the subarray so that the required beam front is launched toward the ground antenna. A

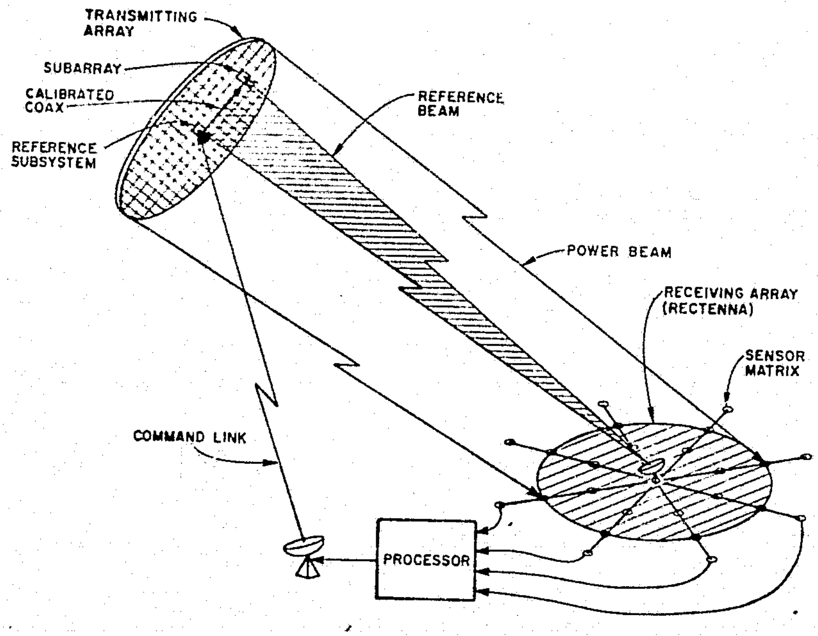

Figure 19 Command and Adaptive Phase Front Control Concepts

similar retrodirective technique is used in other applications [IEEE Trans., 1964], although not with the primary purpose of compensating for structural deflections, which requires that a reference signal be distributed to each subarray.

A number of possible approaches to subarray designs are shown in Figure 20. The slotted waveguide approach is selected because it has very high antenna efficiency while also serving as an efficient means to distribute the microwave power from the converters to the radiating elements. The spacefed array shown in Figure 21 represents a radically different approach to the overall antenna mechanization that was devised to simplify converter repair or replacement by centrally locating them. However mechanical complexity, lower efficiency and need for active heat transfer to a radiator (not detailed) are important disadvantages. A second alternative also shown is a cylindrical array using electrical switching to eliminate the rotary joint to a solar oriented power source. It is too heavy, costly and complex to compete with the recommended planar approach.

Having selected the waveguide approach to antenna design, we proceeded to select material wall thickness and subarray dimensions. The thermal interface between converter and waveguide, shown in Figure 22 for the amplitron, was analyzed to obtain the deflection data shown in Figure 23. This is for a wall thickness of 0.5 mm which is believed to be the minimum produced to date. The aluminum deflection over 5 meters is sufficient to produce a 1% beam power loss at the subarray, while graphite composites can extend out to about 18 meters for a 1% loss. The graphite polyimide is a potentially attractive candidate, being 0.6 the density of aluminum and having a higher maximum temperature (290°C) than either aluminum (175°C) or graphite exoxy

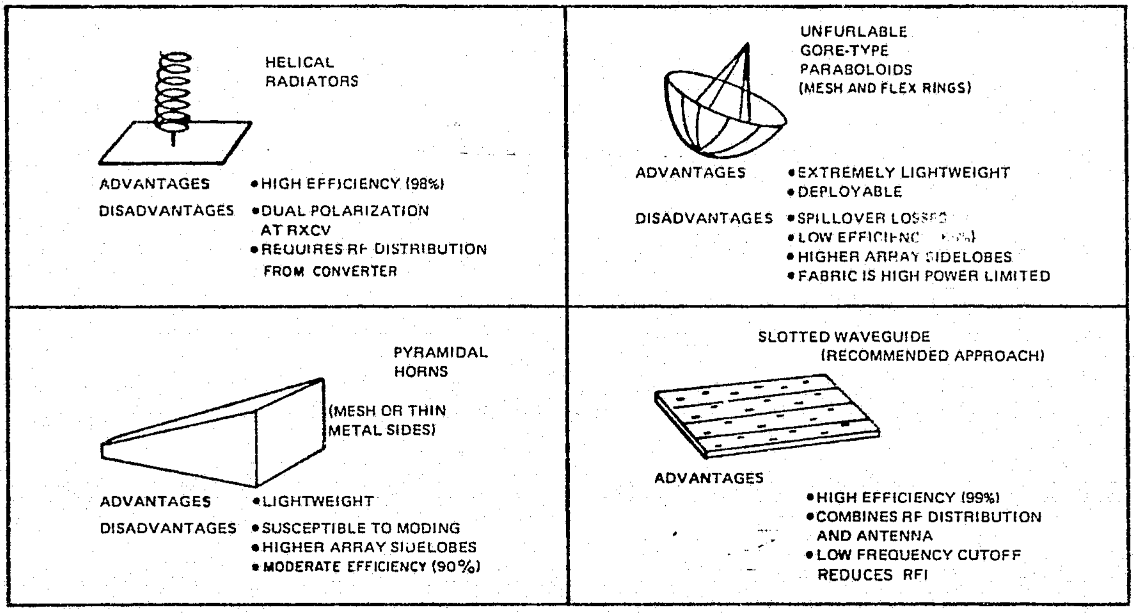

Figure 20 Subarray Types

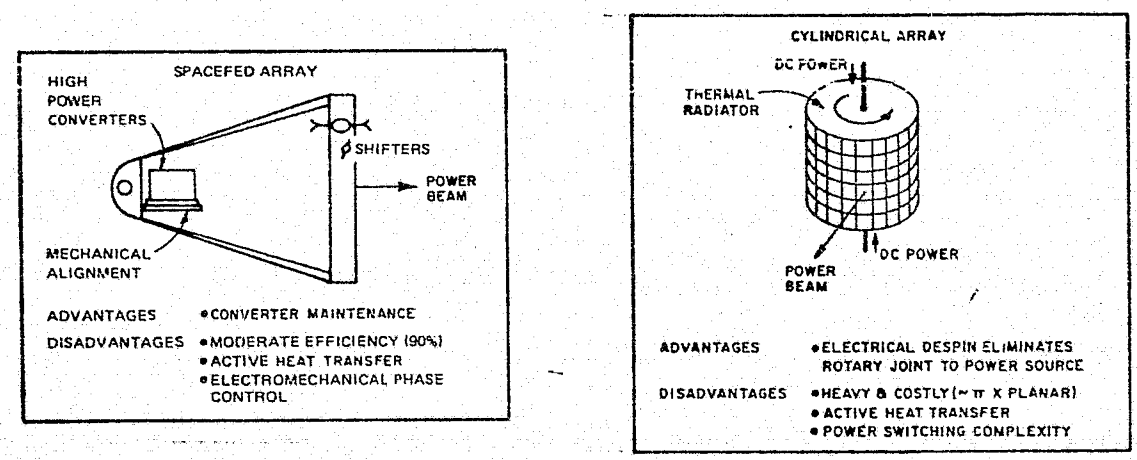

Figure 21 Alternative Array Types

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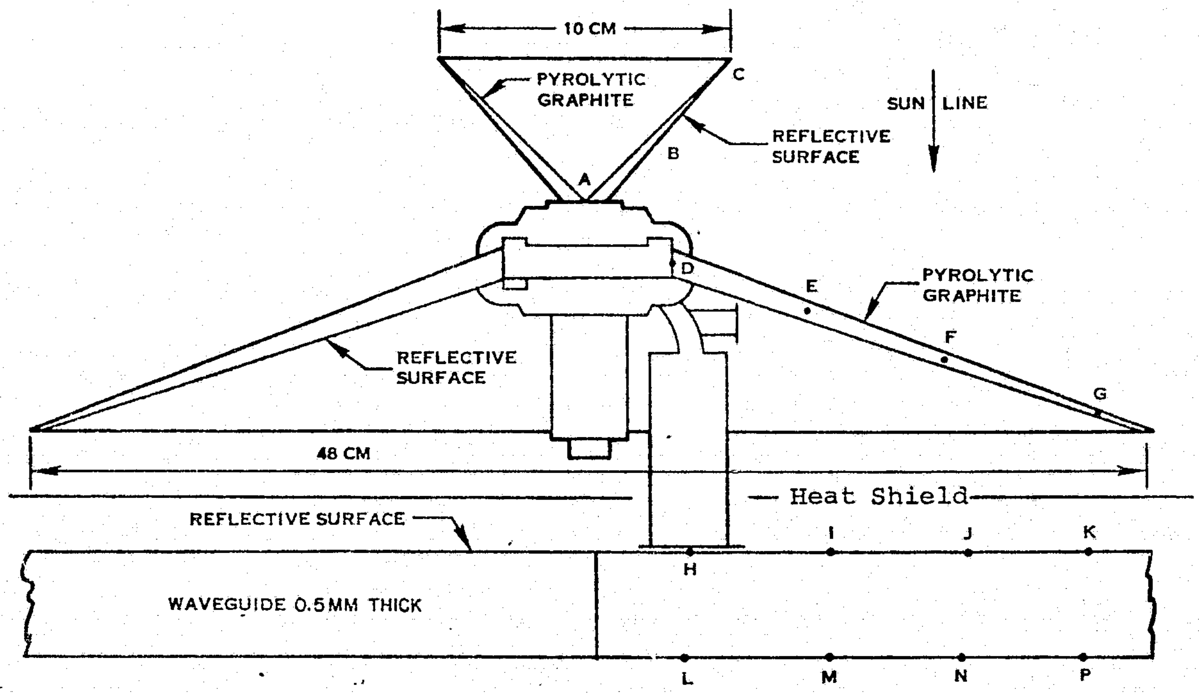

Figure 22 Amplitron Thermal Model

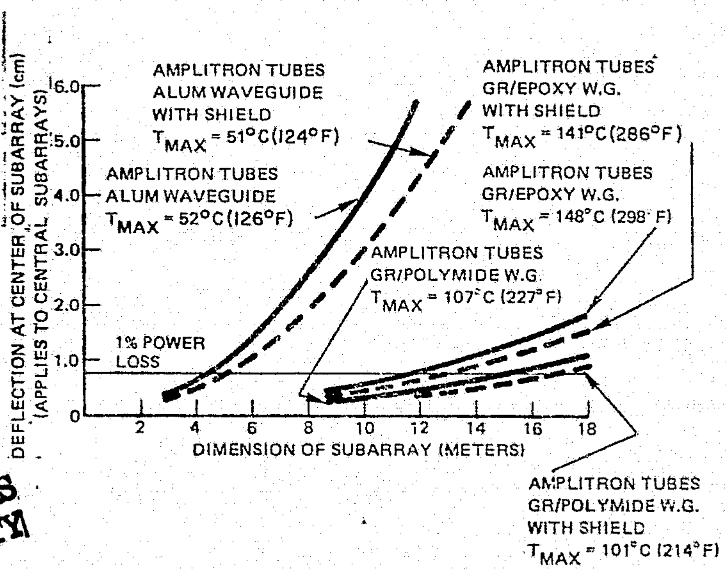

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Figure 23 Subarray Deflection vs Size

(175°C). However, there are questions of the extent of outgassing and its potential effect on the open tube converters as well as questions of stability over 30 years in the space environment. An all aluminum solution must be carried forward until these questions are resolved, and a concept of sectoring the subarray into independent 5-meter segments was devised to alleviate the aluminum deflection problem.

Figure 24 illustrates the tradeoff between capital cost of power lost by increasing subarray size versus capital savings for reduced electronic investment. Subarray dimensions of 18M x 18M were selected because 18M is within the acceptable range and corresponds to the maximum dimensions that can be carried in the Space Shuttle Orbiter, which could be expected to play a key role in early development flights.

The detailed implementation of a subarray with amplitrons is shown in Figure 25. Phase reference electronics are shown, as are the mounting of circuits for power control (crowbars). Screwjacks at the corners provide for mechanical attitude adjustment of the subarray to compensate for installation errors and for deflections that may arise over years of operation. The fully packed tubes with thermal radiators touching represent the highest power density that can be implemented, and so this is a centrally located subarray. Power taper toward the edge of the antenna is achieved by spacing the tubes farther apart. Maximum radiated power for this unit is 7 megawatts, an impressive figure by any earth based standards.

4. MECHANICAL SYSTEMS

Fine pointing by electronic phase control directs the power beam to an accuracy of about 0.04 arc sec (about 10M at Earth), but as noted earlier there is reduced efficiency if mechanical pointing is not reasonably accurate. An error of 1 arc minute corresponding to a power loss under 1% was selected for the design goal and is accomplished with control in elevation and azimuth as shown in Figure 26. The azimuth rotary joint is located at the mast interface with a solar oriented power source for which relative rotation is 360° per day. Additional antenna motion in azimuth and elevation is required to compensate for spacecraft (power source) limit cycling which would nominally be on the order of 1 degree [Glaser, 1974]. The principal disturbance torque on the antenna by far is the frictional torque in azimuth due to contact pressure between the brushes, carrying electric power, and the rotary joint ring. It is estimated at about 10^6 Nm (8×10^5 Ft-Lb). Details of the rotary joints are given in Figure 27. Power is carried across the azimuth interface by silver alloy brushes and slip rings, and across the elevation drive by flexible cable where motion is limited to ± 8 degrees. Orientation drive is nominally by DC torque motor

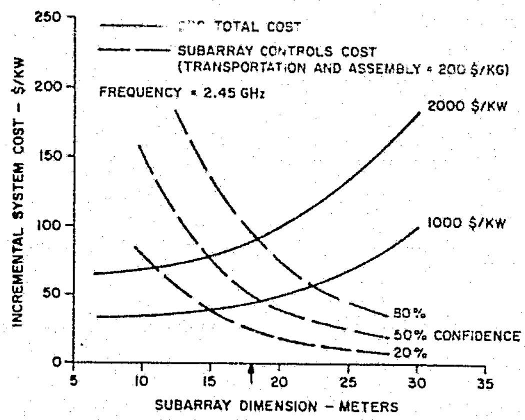


Figure 24 SPS Incremental Cost vs Subarray Size

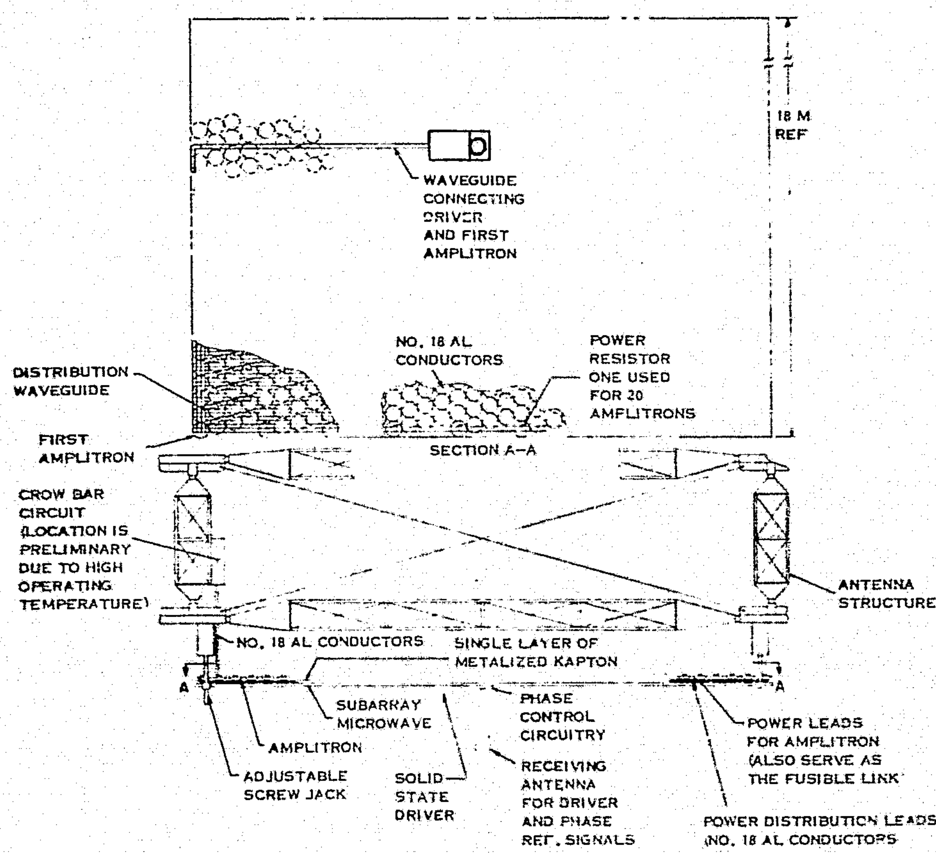


Figure 25 Subarray Layout

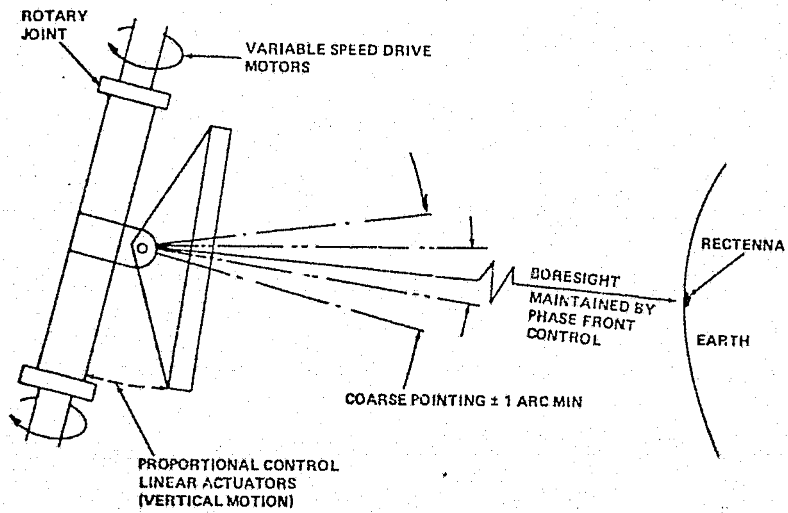
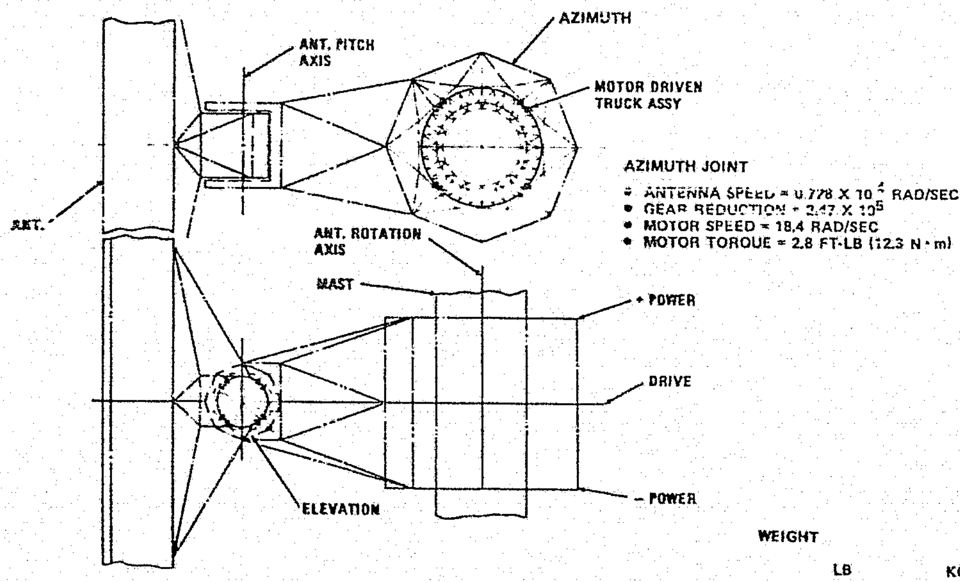


Figure 26 Transmitting Antenna Pointing System



	WEIGHT LB	WEIGHT KG
AZIMUTH		
GEAR BOX & MOTORS	24,065	10,938
DRIVE	2,389	1,086
SLIP RING/BRUSH	1,100	500
SUPPORT	21,196	9,634
TOTAL EACH	48,750	22,158
TWO REQD	(97,500)	(44,316)
ELEV TOTAL	24,300	11,045
TOTAL	121,800	57,361

Figure 27 Rotary Joints

with spur gear drive, but a linear induction drive may prove superior for longer life. Sizing requirements exhibit high torques but surprisingly low power demands:

Azimuth:	1.02×10^6 Nm torque 0.18 hp
Elevation:	2830 Nm torque 1.8 hp

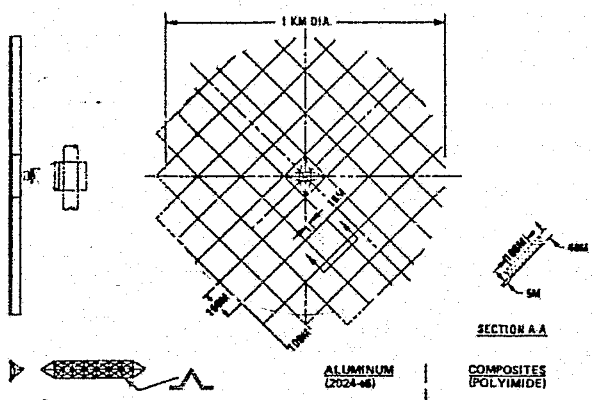
The overall structural concept for the transmitting antenna is shown in Figure 28. Nominal design is 40 meters deep and, depending upon system considerations to be covered later, is about 1 km in diameter. It is assembled in two rectangular grid structural layers. The rectangular grid was found to be less massive than a competing radial spoke design. Primary structure is built up in 108 x 108 x 35 meter bays using triangular grid compression members 18 meters long and 3 meters deep. The secondary structure is used as support points for the waveguide subarrays and is built up as 18 x 18 x 5 meter bays.

The structure to waveguide interface shown in Figure 29 uses three gimballed screwjack assemblies to correct up to a 4 arc min subarray misalignment and a 40.5 cm linear displacement.

Temperature considerations resulted in a choice of a triangular hat construction technique as noted in Figure 30, and a simple locking mechanism to expedite assembly of structural joints is suggested as shown in Figure 31.

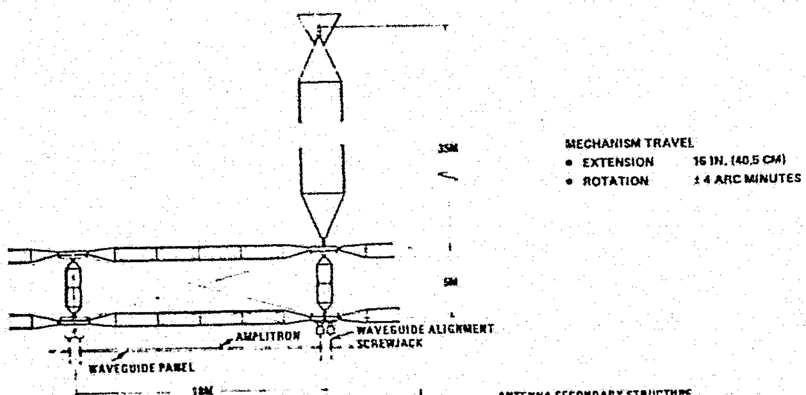
Thermal analysis of the overall structure was a key aspect of the study since distortion and bending impact the error budget for beam phase control. Figures 32 and 33 show the displacements and slopes over the antenna for a full range of sun angle conditions and for aluminum and composite materials. The adaptive phase front control will compensate for the deflection effects, and the screwjacks previously noted can be set to compensate for the average slope error; however, the subarray size must be sufficiently small to keep efficiency (gain) loss tolerable for the deviations about the mean slope that will occur on a daily basis.

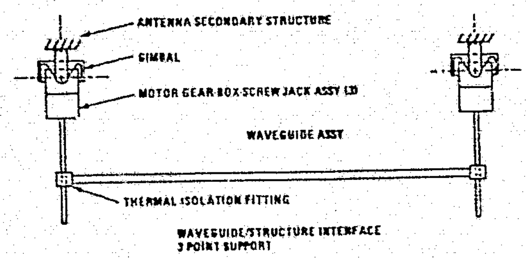
A further result of the thermal analysis was a determination of maximum heat flux density that could be tolerated at the center of the antenna to stay within structural material temperature limits. It was found that microwave converters could be fully packed with their individual radiators touching for any of the materials investigated, with graphite polyimide showing the greatest temperature margin.



	ALUMINUM (2024-46)			COMPOSITES (POLYIMIDE)		
• TEMP, °K	450			560		
• MODULUS OF ELASTICITY, Psi	9 X 10^6			5 X 10^6		
• DENSITY, LB/IN^3	0.101			0.055		
• THICKNESS RANGE, IN.	0.015 TO 040			0.020 TO 0.055		
• WEIGHT	LB	(10^3)	KG	LB	(10^3)	KG
SUBARRAY PRI STRUCT	300		137	207		94
SUBARRAY SEC STRUCT	103		47	65		30
ANT. SUPPORT STRUCT	233		106	157		71
YOKE & MECHANISMS	146		66	122		56
COATINGS	46		21	49		22
AMPLITRON SUPPORT						
CONTOUR CONTROL ACTUATORS	268		122	268		122
AMPLITRON ATTACH STR	51		23	36		16
TOTAL	1147		522	904		411

Figure 28 Antenna Structural Arrangement





WT PER MECHANISM

	LB	KG
SHAFT	20	9.1
WORM	3.8	1.7
MOTOR	5.0	2.3
THERMAL INSULATION	1.6	0.7
GEAR BOX & GIMBAL	8.6	3.0
	44	20

Figure 29 Structure/Waveguide Interface

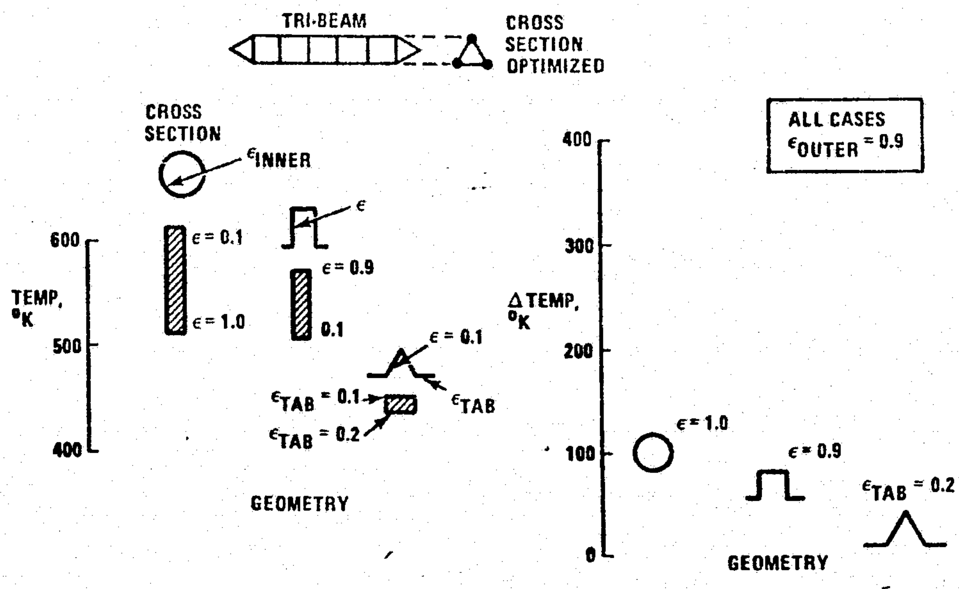


Figure 30 Comparison of Max Temp and Thermal Gradients

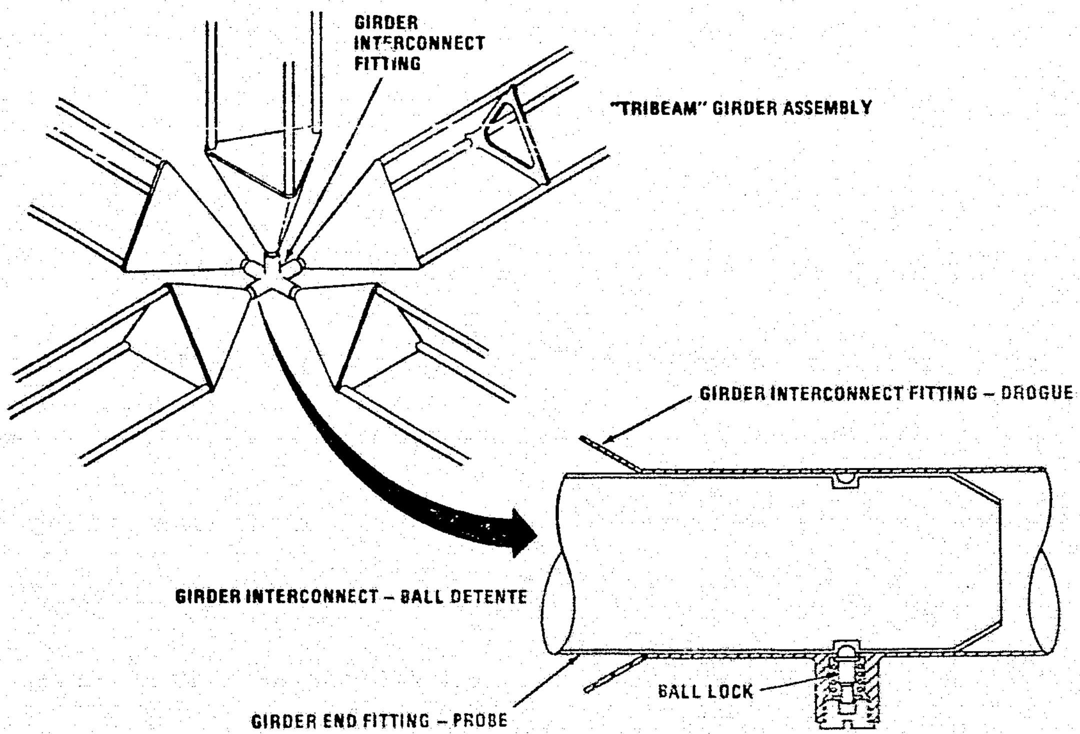


Figure 31 Structural Joints

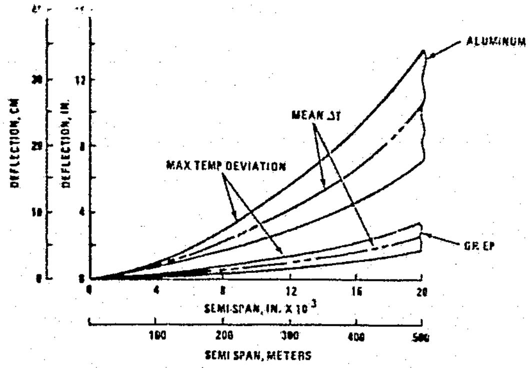


Figure 32 Typical Antenna Deflections Due to Thermal Gradients

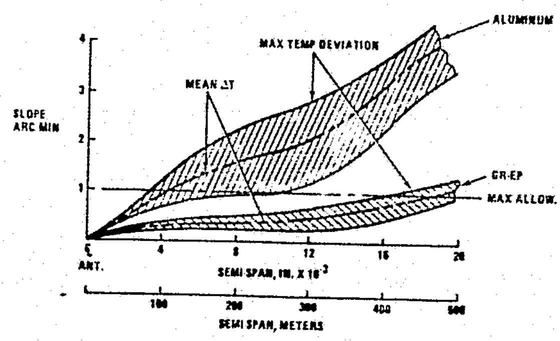


Figure 33 Typical Slopes of Structure Due to Thermal Gradients

5. <u>FLIGHT OPERATIONS</u>

The transportation of a satellite power station with the MPTS to synchronous orbit and the assembly techniques in space are key factors in system cost and technical feasibility. In fact we may expect that these aspects will influence design and tradeoffs to a significant degree, and conversely, expect that the satellite requirements would dictate transportation design to the point of justifying a dedicated system for operational deployment. This study for the most part examined the constraints and cost associated with a system based on the present Space Shuttle Orbiter which would play a key role in satellite development, and a support role in operational deployment.

Two flight plans for assembly and transport to geosynchronous orbit were developed: (1) low altitude assembly and transport to geosynchronous using solar electric propulsion (SEP), and (2) assembly just above the Van Allen belts and transport to geosynchronous using SEP. A complete SSPS using photovoltaic cells was assumed to establish overall time and support requirements, with assembly flow as shown in Figure 34. The mission options with associated transportation performance capabilities are given in Figure 35.

The challenge in packaging concepts is shown in Figure 36, where a prefabricated waveguide is efficiently stowed, but still is short of the ideal packaging density for the shuttle at the waveguide design wall thickness of 0.5 mm. A space manufacturing and assembly approach would reduce the number of flights here, and similarly so for the structure and for the larger and more massive power source as well. A concept suggested for on-orbit manufacturing of structural members to meet this need is shown in Figure 37.

The traffic and fleet requirements for three plans, two at low altitude with different build times and one at high altitude, are given in Figure 38 for an SSPS providing 5 GW of ground power. The overall estimated transportation and assembly costs for these

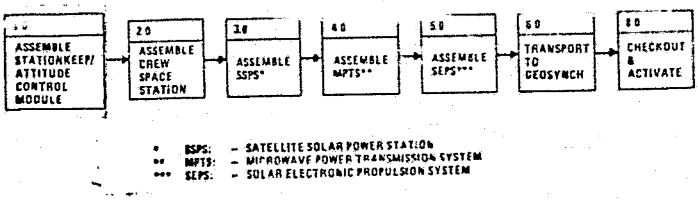


Figure 34 Assembly Functional Flow

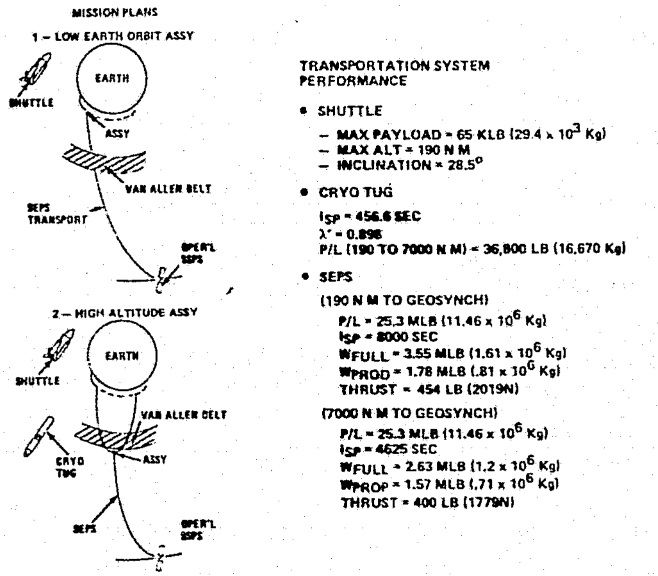


Figure 35 Mission Options

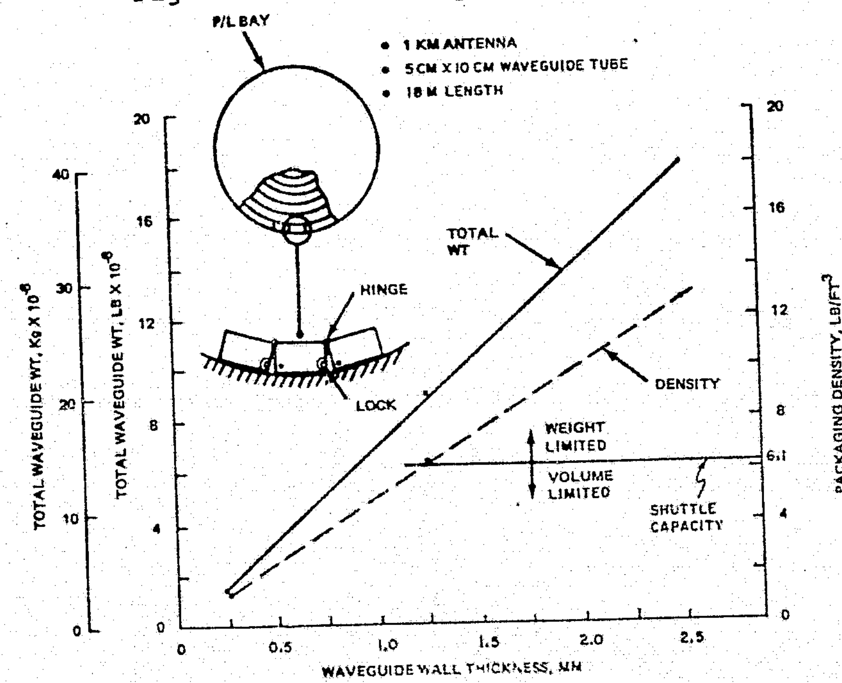


Figure 36 Waveguide Weight and Packaging Density

	CASE 1	CASE 2	CASE 3
• CONDITION			
– GROUND	ASSEMBLE ARTICULATED BEAMS	FORM LONGERONS & CROSS MEMBERS	PRE-PROCESS FLAT STOCK
– IN-ORBIT	DEPLOY	ASSEMBLE	MANUFACTURE
• PACKAGING DENSITY (~SHUTTLE CAPACITY)	0.1 LB/FT^3 (6.1 LB/FT^3)	0.9 TO 75 LB/FT^3 (6.1 LB/FT^3)	100 LB/FT^3 (6.1 LB/FT^3)
• NUMBER SHUTTLE FLTS TO DELIVER ANTENNA STRUCTURE	440	8 TO 49	8
• SUPPORT EQUIPMENT	DEPLOYMENT CANNISTER	24 SPACE STATIONS	8 MFG MODULES

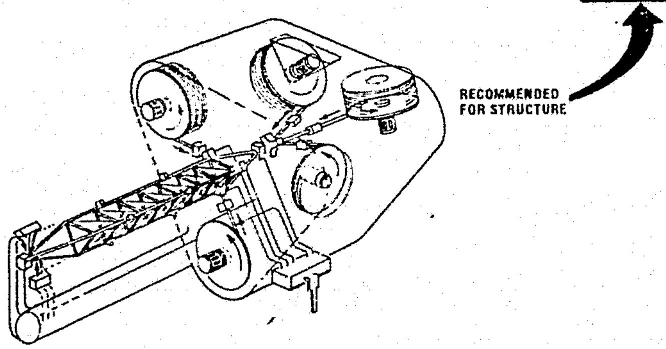


Figure 37 Detail Part Assembly Summary

	FLT PLAN 1	FLT PLAN 2	FLT PLAN 3
• CONDITION			
– ASSEMBLY ALT	190 N M	7000 N M	190 N M
– ASSEMBLY TIME	1 YR	1 YR	2 YR
– DETAIL PARTS	AUTO IN-ORBIT	AUTO IN-ORBIT	AUTO IN-ORBIT
– ASSEMBLY	REMOTE	REMOTE	REMOTE
• FLTS			
– SHUTTLE	491	1348	501
– TUG	–	855	–
– AVG SHUTTLE FLTS/DAY	1.37	3.68	0.7
– AVG TUG FLTS/DAY	–	2.34	–
• FLEET SIZE			
– SHUTTLE	24	59	15
– MANUFACTURE MODULES	8	8	4
– MANIPULATOR MODULES	182	176	91
– CREW SUPPORT MODULES	2	–	2
– TUGS	–	37	–
– SPACE STATION	–	1	–
– CREW TRANSPORT MODULE	–	2	–

Figure 38 Traffic and Fleet Size Summary

options are: Plan 1 - 594 \$/kg, Plan 2 - 1554 \$/kg, Plan 3 - 571 \$/kg. The time value of capital, as described later, would favor the Plan 1 with the short build cycle. The high altitude assembly appears out of the running on cost grounds. However, the low altitude options must make allowance for SEPS solar cell degradation and must protect the SSPS cells while traversing the Van Allen belts over relatively long time periods.

The cost breakdown for Plan 1 in Figure 39 shows that only about 10% is applicable to the orbital assembly task, so that major cost reduction is possible if a more economical basic transportation mode to low earth orbit were developed. If, as forecasted, an unmanned fully reusable, fly back heavy lift launch vehicle (HLLV) with a 180,000 kg payload can be launched at a unit cost comparable to the Shuttle Orbiter, which has a 30,000 kg payload, then the transportation and total costs would approach 125 $/kg and 150 $/kg respectively. Assembly operations of course would still require a manned Shuttle.

6. RECEIVING ANTENNA

A review of options for the antenna design at the ground receiving site quickly confirmed that an array of solid state diode rectifier elements each combined with individual dipole antenna and suitable filter was the only choice combining both high efficiency and low cost. These and other significant factors are noted in a comparison of approaches in Figure 40. This integrated reception-collection-rectification antenna concept is termed a rectenna, and its technology is the farthest advanced of those related to efficient transmission of microwave power. The most recent evidence of this was the achievement of an 82% efficiency at an output power level of 32 kW in a demonstration at the Goldstone, California facility of the Jet Propulsion Laboratory [Raytheon Co., 1975]. This subsystem efficiency is very close to the individual element efficiency plotted as a function of frequency in Figure 41.

Overall construction of the rectenna which covers an area of about 100 km^2 was shown in Figure 1. The panels are tilted to normality with the incoming phase front, but the accuracy need not be great since the individual antenna elements have broad dipole gain patterns; and for the same reason the phase front can be distorted by the atmosphere or ionosphere without appreciably affecting efficiency. Figure 42 shows the detailed organization of the rectenna where the DC power is collected at each element in parallel. At the next level it is summed in a series connection to reach voltage levels at which efficient conversion or distribution can be made. The ground plane is open metal construction for low cost and low wind resistance. Sealing of the rectenna elements within a plastic tube is suggested as a means to achieve economical environmental protection. Principal concern as regards weather phenomena would be damage due to large hailstones and this must be considered in site selection.

The rectenna's large scale demands a very low cost, mass production approach to manufacture of the several billion elements and the supporting structure. Cost estimates for a 2.45 GHz operating frequency are:

Shottky Barrier Diodes	2.84 $\$/m^2$
Rectenna Circuit Assembly	3.26
Supporting Structure and Final Assembly	5.50
	11.60 $\$/m^2$

ELEMENT	NON-RECURRING, $M	FLEET SIZE	RECURRING AMORTIZED OVER 5 SSPS, $M	NO. FLTS	NO. PERSONNEL	OPS COST, $M
SHUTTLE	N/A	24	864	492	–	5,166
RAM SUPPORT MODULE	218	2	16	12	–	12
RAM COM MODULE	283	2	23.5	12	–	12
MANUFACTURE MODULE	288	8	100	–	–	12
FREE-FLYING TELEOPERATOR	5.95	182	45.2	–	546	21.7
CONTROL MODULE	TBD	1	3.2	–	–	1.4
TDRS	230	6	60	–	–	9
SEPS	TBD	1	400	1	–	15.7
	TOTAL		1,511.9			5,249.8

- TOTAL COST (RECUR + OPS) = $6,761.7M
- COST/LB = $270/LB ($594/Kg)
- $/KW = $1352/KW

*ASSUMES $1M/MONTH OVER 1 YR PERIOD FOR FLT OPS SUPPORT

Figure 39 Transportation and Assembly Cost - Plan 1

REQUIREMENT FOR RECEPTION & RECTIFICATION OF SPACE-TO-EARTH POWER TRANSMISSION	ANTENNA APPROACH			
	ARRAY OF CONTIGUOUS HORNS	ARRAY OF CONTIGUOUS REFLECTORS & FEED HORNS	PHASED ARRAY OF SMALL-APERTURE ELEMENTS WITH COMMON MICROWAVE LOAD	ARRAY OF SMALL-APERTURE ELEMENTS WITH INDEPENDENT MICROWAVE LOAD (RECTENNA)
LOW DIRECTIVITY	NO	NO	NO	YES
HIGH COLLECTION EFFICIENCY	<70%	<70%	~100%	~100%
PASSIVE RADIATION OF WASTE HEAT	NO	NO	NO	YES
EASY MECHANICAL TOLERANCE REQUIREMENTS	NO	NO	NO	YES
LOW COST	NO	NO	NO	YES

Figure 40 Comparison of Antenna Approaches

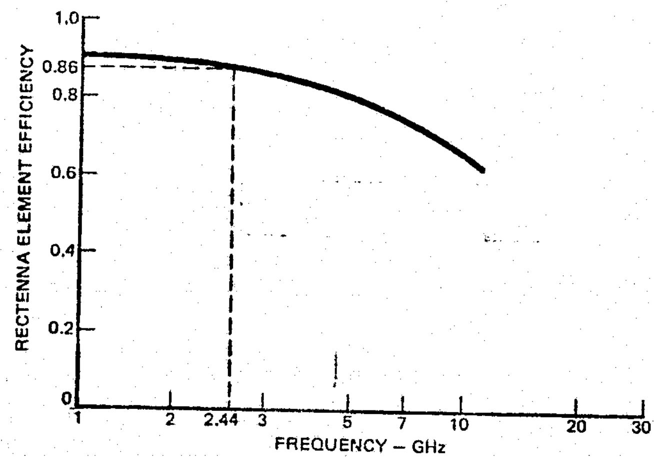


Figure 41 Rectenna Element Efficiency vs Frequency

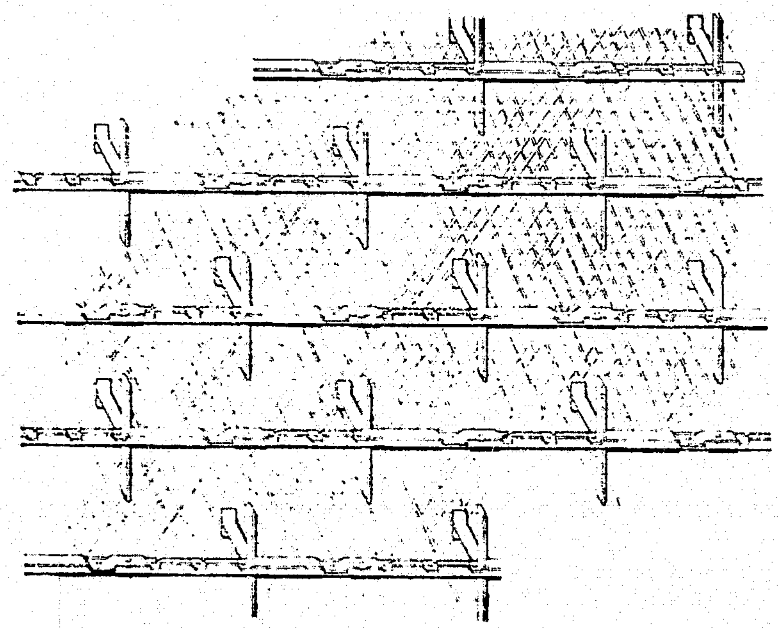


Figure 42 Rectenna Elements

Extension of learning curves for diode production shown in Figure 43 indicate that one cent per diode cost at high quantity can be projected. Power distribution at about 47 \$/kW (2.50 \$/m²) at 5 GW) also is important. The cost factors for real estate and site preparation assuming a generally suitable location has been selected are relatively small.

7. SYSTEMS ANALYSIS AND EVALUATION

Frequency and power output level are the two prime parameters affecting MPTS performance, given the subsystem and component characteristics discussed above. MPTS cost and efficiency together determine its performance, and these can be combined into a single index of capital cost per kilowatt of ground output power if the power source characteristics are included, so that the cost impact of MPTS inefficiency is accounted for. We must also include the orbital transportation and assembly costs which can be more significant than the equipment factory manufacturing costs.

The range of power source and transportation-assembly factors included in the study is shown in Figure 44. The high transportation and assembly cost of 600 \$/kg derives from the Shuttle based estimate, and the low figure of 100 \$/kg, which is below the transportation factor for the HLLV noted earlier, represents a probable lower extreme for a combined transportation and assembly cost for operational systems with deployment extending into the next century.

The power source estimates represent a composite assessment of the range of values appropriate to the 1980's and beyond for solar photovoltaic [Glaser, 1974], solar thermal [Woodcock, 1974] and nuclear [Williams, 1973] technologies, which have been studied elsewhere in decreasing detail in the order given. Points of reference are the cost goals for ground based solar arrays recommended as realistic for the U.S.A. by a National Science Foundation Study [1974], which are 500 \$/kW by 1985 and 200 \$/kW in a subsequent development phase. Other reference points are an estimate of 313 \$/kW for an orbital silicon photovoltaic array with 2:1 concentration ratio and 18% cell efficiency made in the prior feasibility study [Glaser, 1974] and an updated weight estimate of 1.46 kg/kW made in this MPTS study for a 2:1 concentration ratio and 14% cell efficiency. The high values in Figure 44 represent what are thought to be achievable with high confidence in the required time frame.

SPS capital cost as a function of frequency for low and medium level transportation assembly and power source parameters are given in Figures 45 and 46. Plotted are the lowest cost solutions representing tradeoffs between costs of orbital equipment, including transportation and assembly, and the rectenna costs. The latter pertain to an elevation angle of 50 degrees, which would be the case in the Southwest USA. Frequency range has been limited to below 5 GHz because of the increasing susceptibility to rain brownouts above 3 GHz.

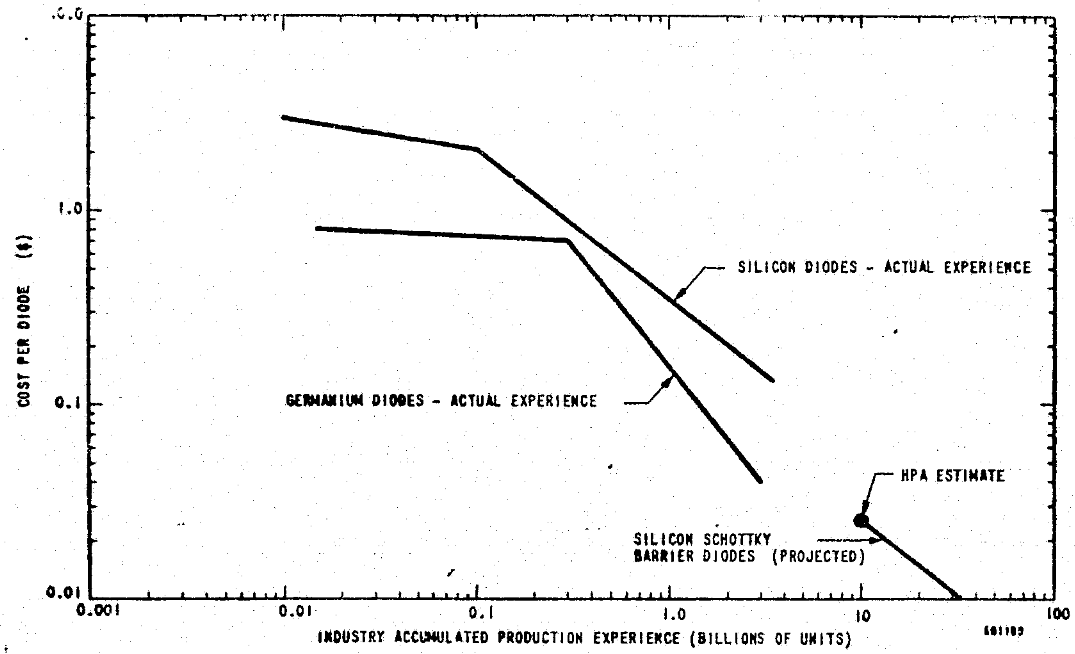


Figure 43 Diode Production Experience

	LOW	MEDIUM	HIGH
ORBITAL TRANSPORTATION AND ASSEMBLY – $/kg	100	300	600
POWER SOURCE WEIGHT – kg/kw – 100% MPTS EFFICIENCY	0.75	1.5	2.5
POWER SOURCE COST – $/kw – NO TRANSPORTATION ASSEMBLY COST – 100% MPTS EFFICIENCY	200	500	1000

Figure 44
Orbital Transportation/Assembly and Power Source Parameters

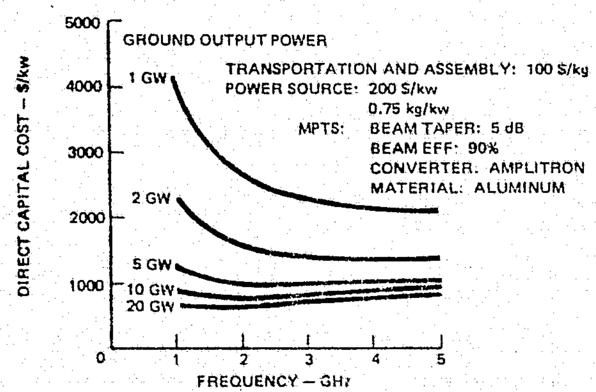


Figure 45 SPS Capital Cost vs Frequency - 100 $/kg

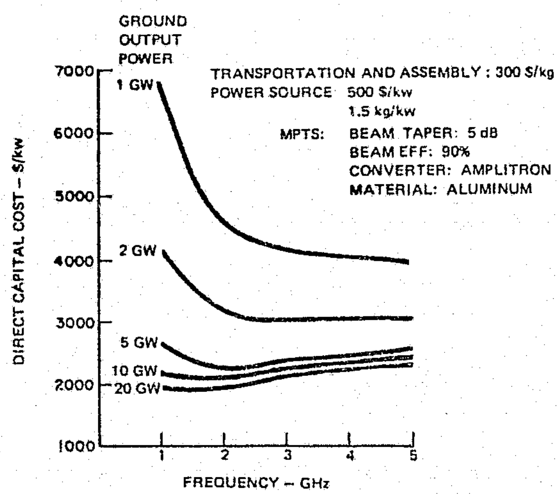


Figure 46 SPS Capital Cost vs Frequency - 300 $/kg

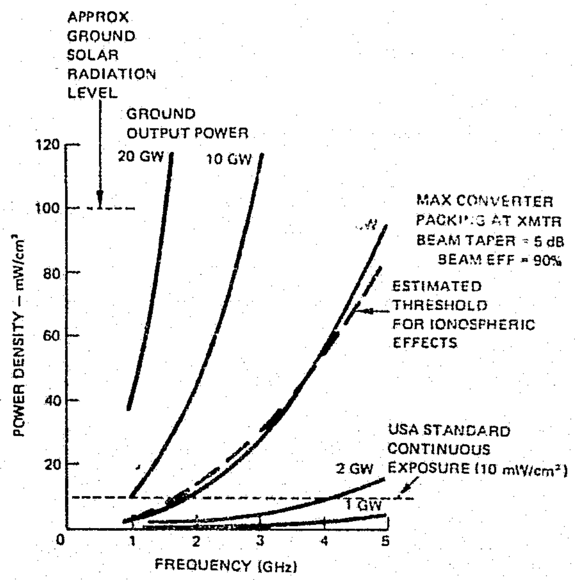


Figure 47 Peak Ground Power Density vs Frequency

The significant trend is to reduced cost at higher power levels which is due to the fact that the rectenna is better utilized as power densities on the ground increase. The relative improvement slows above 5 GW as the basic power source costs dominate. Cost at low power levels trends lower with increasing frequency because the transmitting antenna gain increases with reduced microwave wavelength. At the relatively economical power levels of 5 GW and above, however, there are broad minima around 2 GHz, caused by the dc-rf converter packing limit resulting in a larger transmitting antenna than would otherwise be optimum at higher frequencies.

A critical factor in addition to direct cost to be considered in selecting frequency and power is ground power density, which has implications for biological and environmental effects. Figure 47 shows peak ground power density assuming dc-rf converters are fully packed at the center of the transmitting antenna, an approach which minimizes antenna diameter and thus minimizes ground power density. Reference values are 100 mW/cm^2 for sunlight at ground level and 10 mW/cm^2 for the USA standard for continuous exposure to microwaves. An estimate for onset of ionosphere modification effects, based on scaling from experiments at much lower frequencies [Meltz, 1974], is also shown. Levels above the biological standard could be accommodated (restricting rectenna area and its air space to fly throughs would limit exposure to short periods), and ionosphere modifications probably will be localized and have negligible effect on other users; nevertheless it would be prudent to limit power to levels as low as can be economically useful, such as 5 GW or 10 GW at most, for planning purposes.

Still another key factor to be considered is radio frequency allocation and radio frequency interference. As a general rule, the lower the frequency the more impact there would be on established users of the radio spectrum and the less economically attractive would be an SPS on a cost benefit basis. Specific "natural" frequencies to be avoided if possible are the space hydrogen and hydroxyl emission lines at 1.4 GHz and 1.7 GHz respectively, which are under continuous observation by the radio astronomy community. Although current and planned usage of the spectrum for space activities, including the NASA unified S-band from 2.1 GHz to 2.3 GHz and the communications satellites beginning at 3.7 GHz, could be shifted to other frequencies in the extended time frame needed for an SPS development, it would also be prudent to expedite MPTS development by avoiding these frequencies as well. The recommended choice is the industrial microwave band of 2.45 GHz ± 0.05 GHz. This is cost effective on both a system and DC-RF converter level, as previously shown, provides continuity with prior rectenna development, avoids potential frequency allocation problems, and minimizes impact on other spectrum users.

Users of the spectrum from 2.4 GHz to 10 GHz with sensitive receivers would have to protect themselves with notch filters against the fundamental and up to third or fourth harmonic emissions. High gain antenna (60 dB) radio astronomy observers in view of an SPS would be denied only the basic 2.4-2.5 GHz band if klystrons were utilized as the dc-rf converters. The higher projected noise output of amplitrons, even with filters, would exclude an additional range up to 2.7 GHz; and where the SPS were in the main lobe of a 60 dB antenna, would exclude observations above 1.9 GHz. The amplitron noise estimates are based on measurements of pulsed tubes and as such may be too high, since there is some evidence that continuous wave operation as proposed for MPTS may reduce noise considerably.

The trend of MPTS characteristics at a design center of 2.45 GHz and 5 GW-10 GW power level is shown in Figure 48 for amplitron-aluminum configurations. SPS cost changes little at a given power level so that the taper-beam interception efficiency choice can be made on the basis of such factors as minimum ground power density, reduced land use, minimum antenna weight, etc. We can expect in fact that the modular designs described for the subsystems would lend themselves to configurations tailored for a particular site, with variations in the weight given to the key factors. The 5 GW, 5 dB taper, 90% beam interception case is chosen as the single baseline for further evaluation.

Figure 49 provides a comparison of dc-rf converters and material choices for a 5 GW baseline system. We see that the klystron designs are substantially heavier and more costly as could be expected from the component characteristics provided earlier. For waveguide and structure, the graphite material choice reduces weight but has negligible impact on cost because of an offsetting increase in processing cost relative to aluminum; however, development of manufacturing and assembly concepts, especially for orbital use, could very well shift preference strongly to one or the other material.

GROUND POWER GW	XMTR TAPER dB	BEAM INTERCEPTION %	TRANSMITTING ANTENNA WT – KGX10^6	TRANSMITTING ANTENNA DIA – kM	RECTENNA DIMENSIONS* kM	MAX GROUND POWER DENSITY mW/cm^2
5	5	90	6.2	0.8	11 x 15	17
	10	95	8.3	1.0	10 x 13	22
10	5	90	11.9	1.2	8 x 10	68
	10	95	14.3	1.4	7 x 9	87

*MAJOR AXIS IS FOR ELEVATION ANGLE = 50 DEG

Figure 48 Amplitron-Aluminum MPTS Comparison

TAPER = 5 dB
BEAM EFFICIENCY = 90%

POWER SOURCE – 1.5 kg/kw
– 500 $/kw
TRANSPORTATION ASSEMBLY – 300 $/kg

DC-RF CONVERTER	STRUCTURE & WAVEGUIDE MATERIAL	DC-RF CONVERTER WT KG X 10^6	TRANSMITTING ANTENNA TOTAL WT KG X 10^6	MPTS $/kw	SPS $/kw
AMPLITRON	ALUMINUM	2.6	6.2	700	2300
	GRAPHITE	2.6	5.0	700	2300
KLYSTRON	ALUMINUM	7.3	12.5	1100	2800
	GRAPHITE	7.3	10.8	1100	2800

Figure 49 Comparison of 5 GW Systems

A summary budget of MPTS efficiency is given in Figure 50 showing sets of values appropriate for initial deployment, for nominal design and for goals believed appropriate to a fully matured technology. Detailed estimates and tradeoffs were done in this study at the conservative 58% level.

A direct capital cost evaluation for a complete SPS 5 GW baseline system is given in Figure 51 for the range of power source characteristics and as a function of orbital transportation and assembly costs. All estimates are in 1975 dollars. The principal uncertainties are seen to be the power source and transportation-assembly costs, with MPTS efficiency following and MPTS ground manufacturing cost last in importance. The relative impact on the cost of energy in mills/per kWhr of these factors is similar, as shown in Figure 52. It was assumed in computing energy cost that a lump sum funding is obtained for ground construction at program start and a second lump is obtained for transportation-assembly at initial launch. Inflation is not considered. Interestingly enough, possible variations in annual rate of return and the build cycle for an SPS both have energy cost impacts equal to or more important than the MPTS efficiency range, as indicated in Figures 53 and 54.

Energy cost projections for nuclear and fossil plants run in the range of 25 to 45 mills per kWhr on the basis of an 80% load factor. Assuming the SPS should be competitive in this order of magnitude, a set of characteristics for the average of the many operational systems needed to assume a substantial share of the USA energy budget could be as given in Figure 55. The power source and transportation-assembly parameters are believed

	INITIAL	GOAL	NOMINAL
POWER DISTRIBUTION	96	97	96
DC-RF CONVERTER	85	90	87
PHASE CONTROL	95	97	96
ATMOSPHERE	99	99	99
BEAM COLLECTION	90–95*	90–95*	90–95*
RECTENNA	84	90	87
POWER INTERFACE	93	95	94
TOTAL	54–57	65–68	58–62

*DEPENDS ON TRADEOFF OF COSTS, LAND USE, POWER DENSITY LIMITS. TAPER OF POWER DISTRIBUTION ON ORBIT 5 DB LIMIT IS 90%, 10 DB LIMIT APPROACHES 95%.

Figure 50 MPTS Efficiency Budget

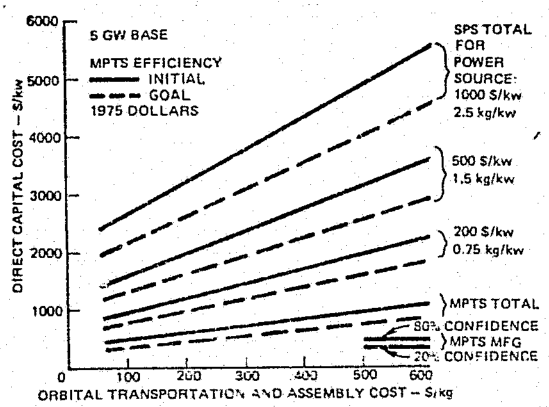


Figure 51 SPS Capital Cost for Various Power Source Characteristics

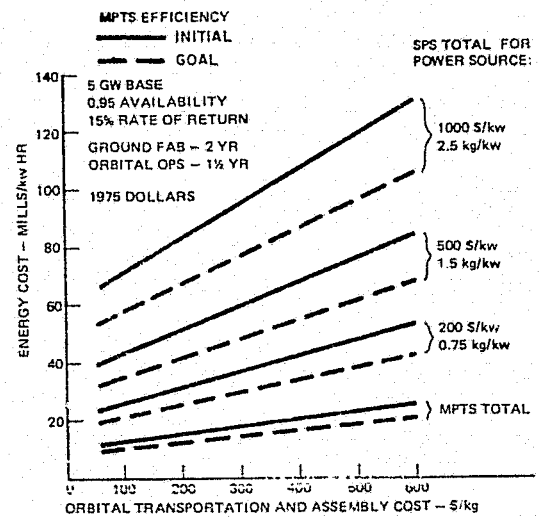


Figure 52 SPS Energy Cost for Various Power Source Characteristics

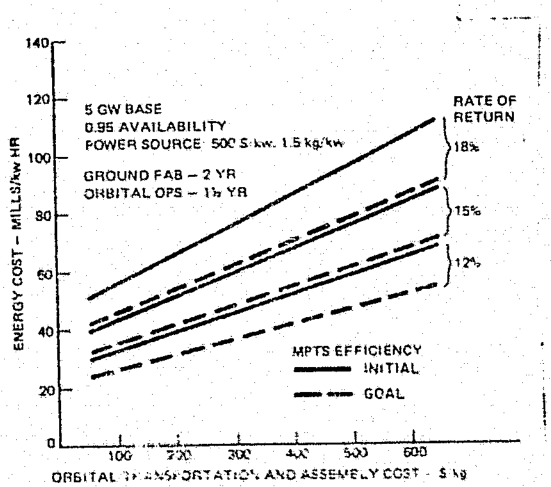


Figure 53 SPS Energy Cost for Various Rates of Return

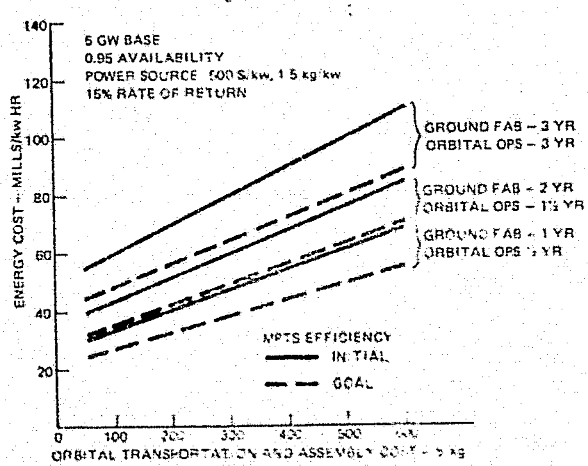


Figure 54 SPS Energy Cost for Various Construction Cycles

ORBITAL TRANSPORTATION AND ASSEMBLY COST	200 $/kg
POWER SOURCE	
MANUFACTURING COST	350 $/kw (TO MPTS)
SPECIFIC WEIGHT	1 kg/kw (TO MPTS)
MPTS	
EFFICIENCY	60%
MANUFACTURING COST	350 $/kw (TO POWER GRID)
ORBITAL WEIGHT	1.2kg/kw (TO POWER GRID)
SPS BUILD AND DEPLOY CYCLE	3 YR

Figure 55 Suggested Nominal Values for SPS and MPTS

compatible in the sense that they probably involve about equal risk for achievement in the required time frame. The set represents a 1500 $/kW SPS capital cost, of which 600 $/kW is attributed to MPTS, and results in 45 mills/kWhr for 80% load factor and 15% annual rate of return.

8. CRITICAL TECHNOLOGY

An assessment of technology status and risk was made and a ranking was established to help guide future development of the MPTS concept. The approach used is described in Figure 56. The work breakdown structure (WBS) developed for the evaluation is shown in Figure 57 together with the appropriate numerical rankings in each block. For items outside the normal purview of MPTS the assessment was made primarily for the impact on the MPTS. The status and rankings should be re-assessed periodically as further in-depth studies are conducted and technology development progresses. Description of all the SPS category 4 items involving relatively high risk is beyond the scope of this discussion, but a review of the hardware items to be given highest priority is in order. These are the dc-rf converters and filters, materials, phase control subsystems, waveguide and structure.

The dc-rf converters contribute the most power losses in the MPTS; they must have excellent phase stability; and their noise output must be low. The amplitron offers the greater promise for long life, high efficiency, low cost and low weight at lower risk than the klystron. A similar CFA device, the magnetron, has demonstrated the appropriate unit cost in million quantities, and in particular cases has shown 90% efficiency; however it is most important that an amplitron design show at least 85% efficiency, good phase stability and acceptable noise level while operating under environmental conditions appropriate to MPTS.

The role of non-metallic materials such as graphite composites for waveguide and structures depends upon their outgassing properties and long term stability in the space environment, and these aspects must be investigated. The outgassing can interfere with dc-rf converters operating open jacketed to save weight and reach long life. Graphite polyimide, for example, has great potential for reducing transmitting antenna weight, simplifying subarray design by providing great dimensional stability and providing a substantial high temperature safety factor at the center of the transmitting antenna.

		RISK RATING				
		1	2	3	4	5
		IN USE	IN DEVELOPMENT	ON THE TECHNOLOGY FRONTIER	CONCEPTUAL	INVENTION
STATUS ANTICIPATED WITH. a) SPECIFIC MPTS-FUNDED PROGRAM b) OTHER KNOWN PROGRAMS	TECHNOLOGY	FULLY DEVELOPED	PARTLY DEVELOPED	KNOWN BUT NOT DEVELOPED	NOT KNOWN, CHANCE OF IT BECOMING KNOWN IN TIME FOR MPTS IS GOOD	NOT KNOWN, CHANCE OF IT BECOMING KNOWN IN TIME FOR MPTS IS POOR
	HARDWARE	OFF-THE-SHELF ITEM OR PROTOTYPE AVAILABLE HAVING REQUIRED FUNCTION, PERFORMANCE & PACKAGING	FUNCTIONALLY EQUIVALENT HARDWARE IN USE (OPERATIONAL)	FUNCTIONALLY EQUIVALENT HARDWARE IN DEVELOPMENT	NO HARDWARE IN USE OR DEVELOPMENT BUT DEVELOPMENT IS PROBABLE	HARDWARE WILL NOT BE AVAILABLE UNLESS A BREAKTHROUGH OR INVENTION IS DEVELOPED
PROBABILITY OF DEVELOPMENT COMPLETION WITHIN SCHEDULE AND COST		CERTAIN (ALREADY EXIST)	VERY HIGH	HIGH	LOW	VERY LOW

Figure 56
Technology and Hardware Development Risk Rating Definition

Phase control subsystems must perform with high accuracy to keep beam scattering losses at acceptable levels and also to point the power beam at the center of the rectenna for both high efficiency and safety. The tolerable errors are sufficiently small that early development and demonstration is mandatory

The slotted waveguides represent a substantially high risk because of the need for low weight, stable propagation with small phase errors, low cost manufactureability, probably in orbit, and need for orbital assembly. The design of a dc-rf converter-waveguide interface suitable for on-orbit assembly is considered in this category, and it involves all the key technologies noted. Alternatives to the conventional rectangular waveguide construction may prove advantageous in this application and should be explored.

Finally, the structure represents a high risk until its materials, thermal distortion and produceability are established.

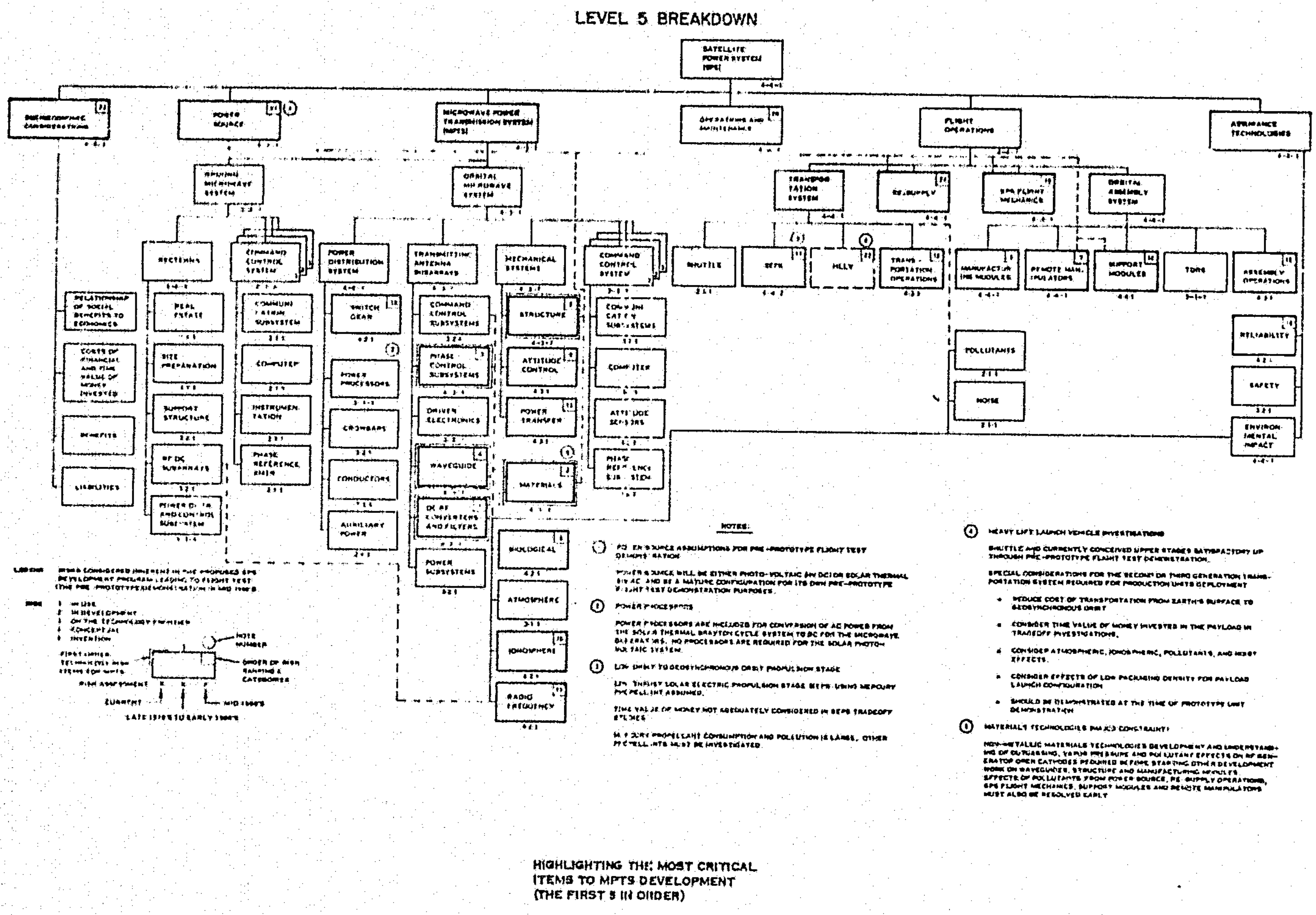


Figure 57 Satellite Power System Technology Risk Assessment

9. CRITICAL TECHNOLOGY AND TEST PROGRAM

A critical technology and test program was formulated to lead from ground tests to orbital tests and so provide a base upon which to plan and build a pilot plant.

Primary objectives for the ground test program are designed to provide substantive data relating to three fundamental issues for MPTS: technical feasibility, safety, and radio frequency interference. Primary objectives are:

a. Adaptive and commanded phase front control accuracy (feasibility issue).

b. System control performance for start-up, shut-down, transients, failure mode protection and recovery (safety issue).

b. Amplitude and spectra of random noise and harmonic output of transmitting array and rectenna (RFI issue).

The site examined in some detail for the ground demonstration was the JPL Venus Station where a rectenna demonstration and test facility have been installed. This has potential advantages in making possible the use of existing facility, power source and data instrumentation. However, this is an example only. A more extensive site survey than possible in this study should be taken in the future.

A functional block diagram for the test is shown in Figure 58. The three test phases increase the capability of the equipment, culminating in a test over a range of about 10 km involving rectenna subarrays similar to those planned for the operational configuration.

The critical development areas identified that bear directly on the ground demonstration are the dc-rf converter and phase control technologies The amplitron was used as the example for the dc-rf converter. Before hardware effort could begin the klystron will require additional study to obtain a solution to the heat transfer problem and to better define characteristics for a maximum efficiency tube.

The program schedule is shown in Figure 59. The demonstration system is complete through Phase III in six years from go-ahead, with each phase design and installation taking two years. The critical technology development is presumed to start concurrently and is planned to have achieved a technical maturity with acceptable risk at each of the Critical Design Review (CDR) milestones sufficient to warrant release of major procurement items for ground demonstration phases. Delays in the technology program will stretch out the ground demonstration proportionally.

The rough order of magnitude costs (ROM) expressed in 1975 dollars are given in Figure 60.

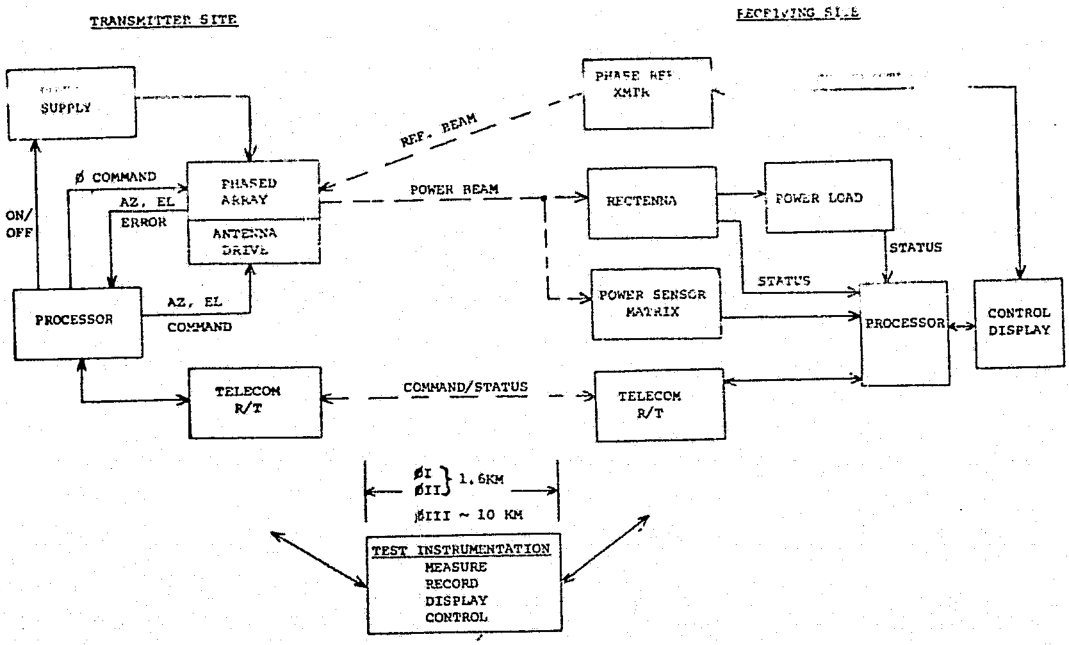


Figure 58
MPTS Ground Test Functional Block Diagram

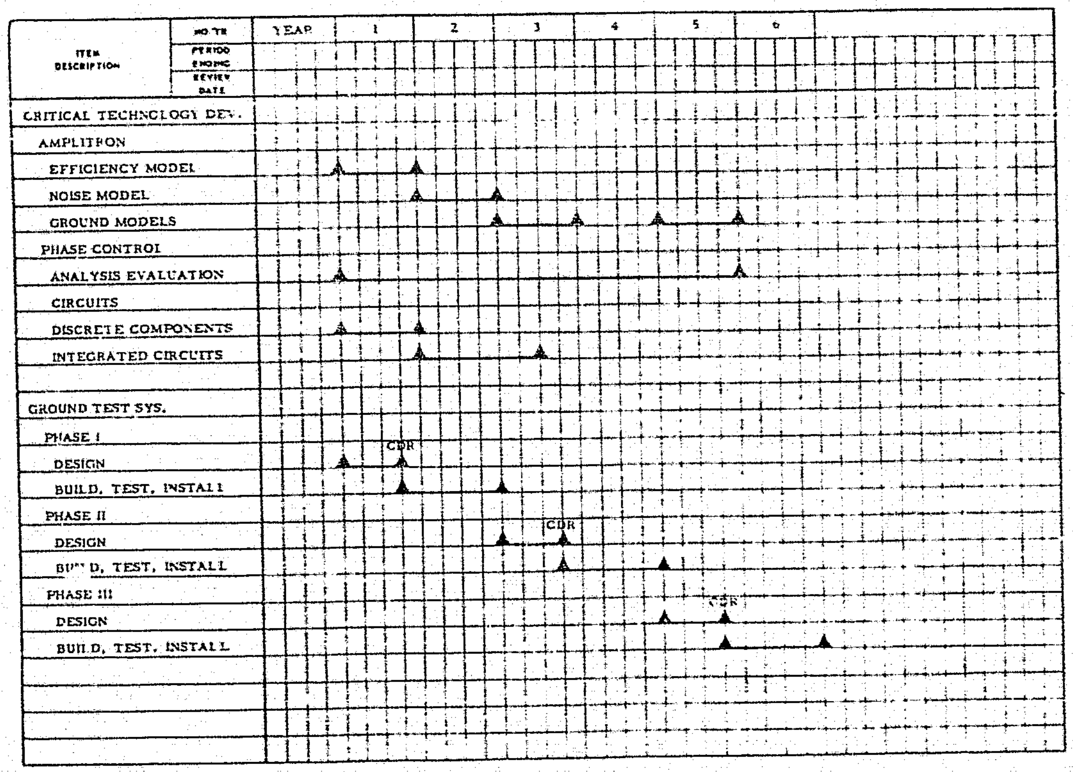


Figure 59
MPTS - Critical Technology Development and Ground Test Program

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Year	1	2	3	4	5	6	Total
Critical Technology							
Amplitron	480	600	435	435	435	435	2820
Phase Control	350	435	330	240	240	-	1595
Ground Test	2390	2470	2190	3300	5325	7045	22720
Total	3220	3505	2955	3975	6000	7480	27135

Figure 60
1975 Dollar ROM Costs, $K, for Critical Technology
and Ground Test Program

The orbital test program is planned to accomplish the successful demonstration of the mandatory and the highly desirable objectives given in Figure 61. Some related intermediate benefits are as shown. The microwave power transmission system related hardware is shown as microwave payload in the figure.

In order to scope the effort involved in meeting the objectives of Figure 61, an approach using an orbital test facility was taken. An orbital test facility was sized considering the power densities desired both in the ionosphere (50 mW/cm^2) and on the ground (20 mW/cm^2). The high antenna angular rates encountered at altitudes of 300 km to 500 km will pose design and operational problems not present at geosynchronous altitudes. It should be emphasized that the quantities of equipments deemed appropriate for the orbital test program are at this time uncertain. Further in-depth investigations should be conducted from which the quantities and scope should be progressively revised. In particular, those objectives associated with the high power microwave beam effects on the ionosphere warrant in-depth investigation and independent assessment. This should be done before accepting them as requirements that will play a major role in formulating the orbital test program.

Figure 62 gives the mission schedule for the orbital test program. Missions 2 through 11 deal with the Low Earth Orbit (LEO) orbital test facility (OTF). Mission 1 requires a satellite at geosynchronous altitudes.

The critical technology (ground based part of flight test program) schedule is shown in Figure 63 and a summary of the MPTS Orbital Test Program costs including technology is given in Figure 64. A management and integration charge of 40% has been applied to the non-Shuttle costs for the prime or integrating contractor role. A 20% contingency is placed on the final figure.

Mission Class	Objectives: Mandatory	Objectives: Highly Desirable	Microwave Payload	Intermediate Benefits
Geo-synchronous	• dc-rf Converter Starting and Operation • High voltage plasma inter-action	• Ionosphere Effects on Pilot Beam • Interferometer Accuracy • Orbital Life Test	• DC-RF Converter • 18 Meter Interferometer • Particle De-tectors	• Communications • Bistatic Radar • Ionosphere Data • Observation of LEO Sorties Effects
Low Earth Orbit (LEO) Sorties	• Zero "G" Mfg. and Assembly Flow De-velopment - Structure - Microwave - Interface • Operations and Mainten-ance Devel-opment • Initial Veri-fication of Cost and Schedule Projections	• Controllability Demonstration • Thermal Cycling Effects - Large Structures • Preprototype Building Block • Orbital Life Test • Upper Ionosphere Heating Effects	• Build-up to 18M x 18M Power Sub-arrays • Spares to be provided along with Command-Control Sub-array and Or-bital Support Equipment • Juxtaposition-ing to be possible	• Communications • Bistatic Radar - Earth - Planetary • Orbital Microwave Power Transfer • Ionosphere Data

Figure 61 Microwave Orbital Test Program

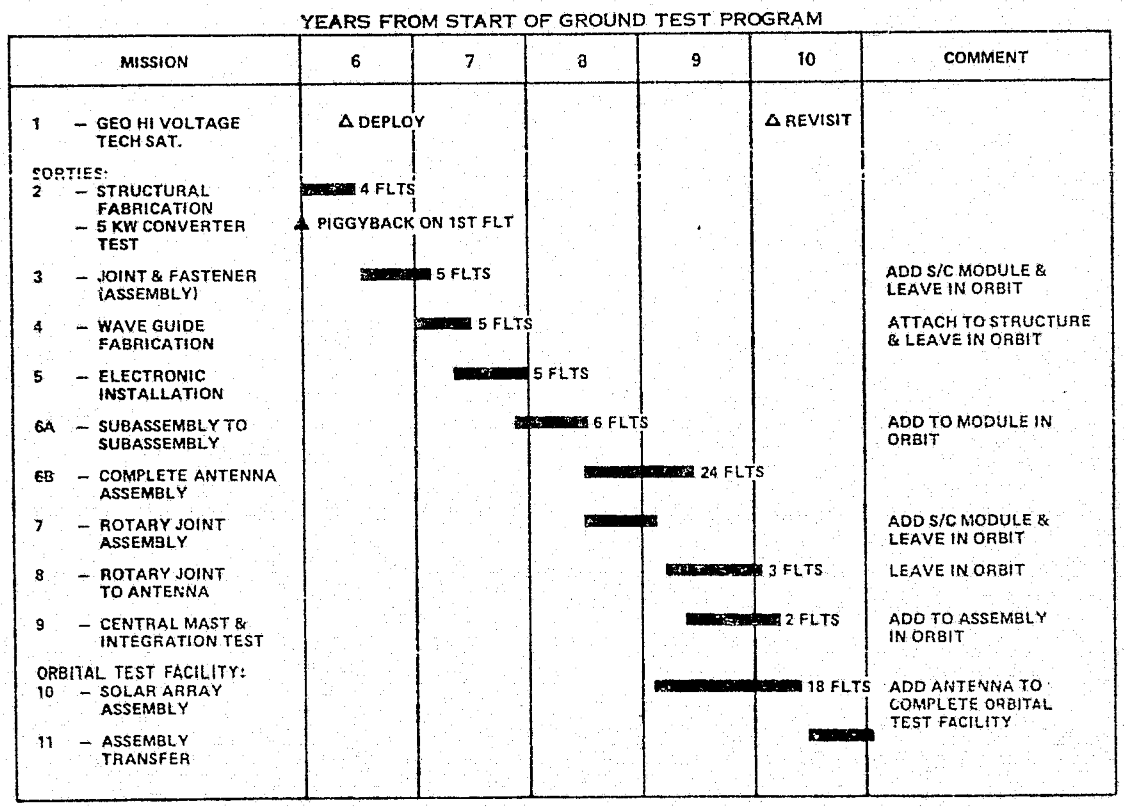

Figure 62 Mission Schedule

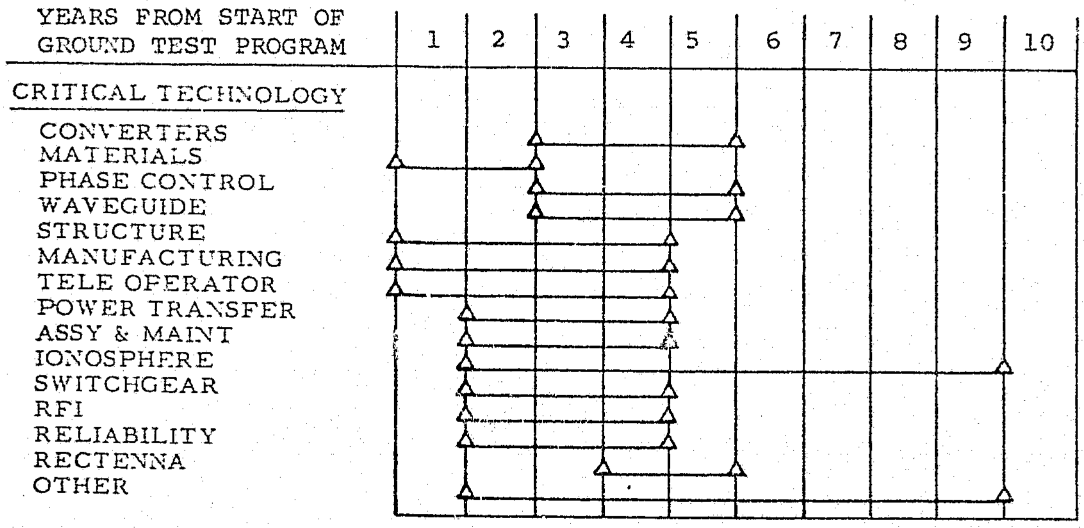

Figure 63 -- Critical Technology Schedule

	YEARS FROM START OF GROUND TEST PROGRAM 1	2	3	4	5	6	7	8	9	10	TOTAL
CRITICAL TECHNOLOGY	27	59	77	109	13	9	8	8	8		318
GEOSATELLITE			17	17	25	37					96
ORBITAL TEST & FACILITY				50	344	536	610	620	627	265	3052
TOTALS	27	59	94	176	382	582	618	628	635	265	3466

* INCLUDES MANAGEMENT AND INTEGRATION (40%), SHUTTLE COSTS, AND CONTINGENCY (20%)

Figure 64
MPTS Orbital Test Program ROM Cost Summary*
(Rough Order of Magnitude in Millions of 1975 Dollars)

10. RECOMMENDATIONS FOR ADDITIONAL STUDIES

Recommendations for early further in-depth studies complementing the technology program are:

a. Analyze transient thermal effects on the transmitting antenna structure, waveguide and electronics as it passes in and out of eclipse to determine impact on controllability and materials selection.

b. Analyze power beam ionospheric effects to estimate impact on other users and provide a detail model for phase front control simulation.

c. Model closed loop phase front control to better estimate error budget and performance under transient conditions.

d. Determine special requirements for multiple (~100) stations relating to spacing in orbit and on the ground, control, frequency selection and interference.

e. Detail alternate uses and intermediate benefits of MPTS and potential impact on its design and development.

f. Investigate ways of reducing transportation and assembly costs by a better synthesis of launch vehicle, assembly and equipment technologies.

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